Particle Physics Phenomenology
12. Various applications and the road ahead

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QCD at LHC

LHC is a QCD machine:

- hard processes initiated by partons (quarks, gluons),
- associated with initial-state QCD corrections (showers etc.),
- underlying event by QCD mechanisms (MPI, colour flow),
- even in scenarios for physics Beyond the Standard Model (BSM) production of new coloured states often favoured (squarks, KK gluons, excited quarks, leptoquarks, . . .).

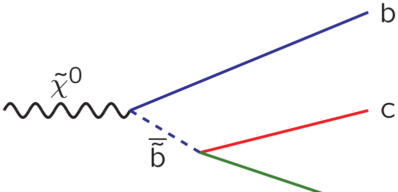
BSM physics can raise "new", specific QCD aspects.
Here we study

1. R-parity violation in Supersymmetry,
2. R-hadron formation in Supersymmetry,
3. parton showers and hadronization in Hidden Valleys,

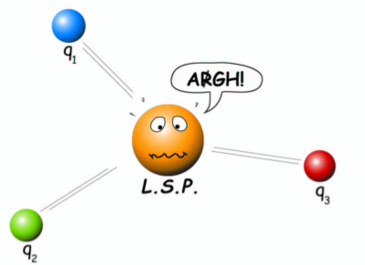
all implemented in PYTHIA 8.

1. *R*-parity violation in SUSY

Baryon number violation (BNV) is allowed in SUSY superpotential.
Alternatively lepton number violation, but proton unstable if both.
BNV couplings should not be too big, or else large loop corrections
$\Rightarrow$ relevent for LSP (Lightest Supersymmetric Particle).



Note: $m(\overline{\tilde{\mathrm{b}}}) > m(\tilde{\chi}^0)$



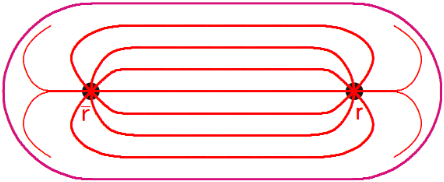
What about showers and hadronization in decays?

P. Skands & TS, Nucl. Phys. B659 (2003) 243;

N. Desai & P. Skands, Eur.Phys.J. C72 (2012) 2238

The Lund string

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**

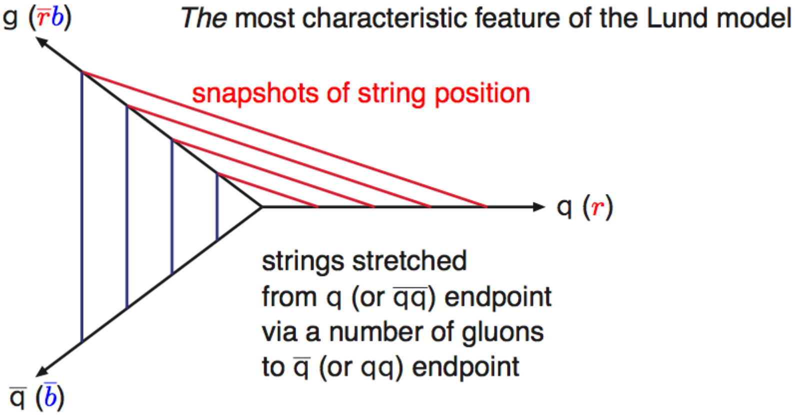


by self-interactions among soft gluons in the "vacuum".

Gives linear confinement with string tension:
$F(r) \approx \mathrm{const} = \kappa \approx 1\ \mathrm{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

Separation of transverse and longitudinal degrees of freedom
$\Rightarrow$ simple description as 1+1-dimensional object – **string** – with Lorentz invariant formalism

The Lund gluon picture

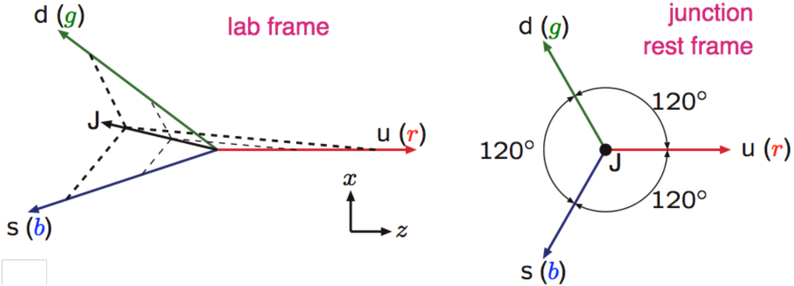


Gluon = kink on string, carrying energy and momentum

Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$, $\rightarrow 2$ for $N_C \rightarrow \infty$

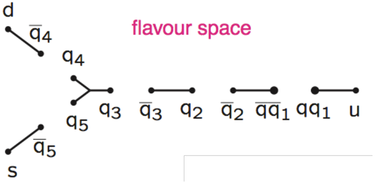
The junction

What string topology for 3 quarks in overall colour singlet?
One possibility is to introduce a **junction** (Artru, 't Hooft, ...).

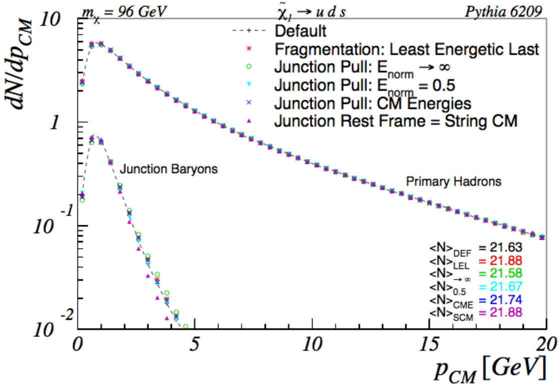


Junction rest frame = where string tensions $\mathbf{T}_i = \kappa\, \mathbf{p}_i/|\mathbf{p}_i|$ balance
$= 120^\circ$ separation between quark directions.
This is not the CM frame where momenta $\mathbf{p}_i$ balance,
but in BNV decay no collinear singularity between quarks,
so normally junction is slowly moving in LSP rest frame.

Junction hadronization

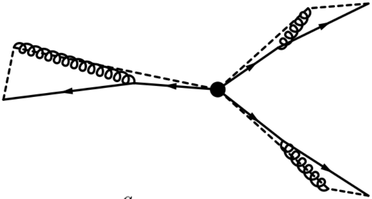


Each string piece can break, mainly to give mesons. Always one baryon around junction; junction "carries" baryon number.

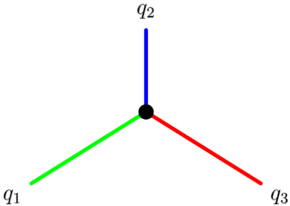


Junction baryon slow $\Rightarrow$ "smoking-gun" signal.

The junction and dipole showers



Normal showers:
each parton can radiate.



Dipole showers: each *pair* of partons, with matching colour–anticolour, can radiate, with recoil inside system.
But here no simply matching colours!

Solution: let each three possible dipoles radiate, but with half normal strength.
Gives correct answer collinear to each parton, and reasonable interpolation in between.

2. *R*-hadron motivation

Now different tack: *R*-parity conserved.

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino.
Squarks and gluinos are unstable and decay to LSP,
e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{q}}\overline{\mathrm{q}} \to \mathrm{q}\tilde{\chi}\overline{\mathrm{q}}$.

Alternative SUSY: gluino LSP, or long-lived for another reason.

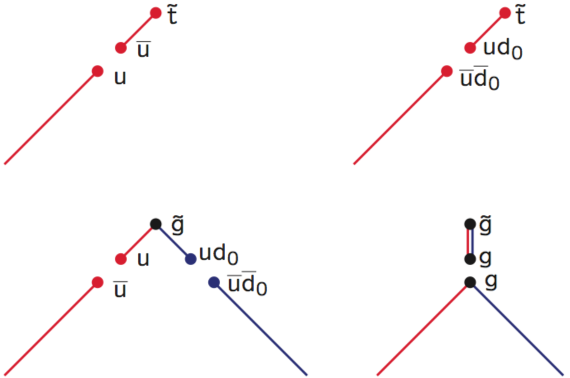
E.g. Split SUSY (Dimopoulos & Arkani-Hamed):
scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.

More generally, many BSM models contain colour triplet or octet particles that can be (pseudo)stable: extra-dimensional excitations with odd KK-parity, leptoquarks, excited quarks, ...

$\Rightarrow$ PYTHIA allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{\mathrm{g}}$, giving $\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}$, $\tilde{\mathrm{g}}\mathrm{uud}$, $\tilde{\mathrm{g}}\mathrm{g}$, . . . ,
- colour triplet charge $+2/3$, like $\tilde{\mathrm{t}}$, giving $\tilde{\mathrm{t}}\overline{\mathrm{u}}$, $\tilde{\mathrm{t}}\mathrm{ud}_0$, . . . ,
- colour triplet charge $-1/3$, like $\tilde{\mathrm{b}}$, giving $\tilde{\mathrm{b}}\overline{\mathrm{c}}$, $\tilde{\mathrm{b}}\mathrm{su}_1$, ...

R-hadron formation



Squark fragmenting to meson or baryon

Gluino fragmenting to baryon or glueball

Most hadronization properties by analogy with normal string fragmentation, but glueball formation new aspect, assumed $\sim 10\%$ of time (or less).

R-hadron interactions

R-hadron interactions with matter involve interesting aspects:

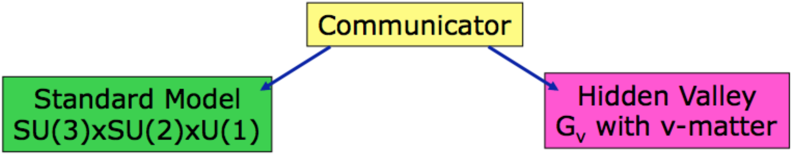
- $\tilde{\mathrm{b}}/\tilde{\mathrm{t}}/\tilde{\mathrm{g}}$ massive $\Rightarrow$ slow-moving, $v \sim 0.7c$.
- In R-hadron rest frame the detector has $v \sim 0.7c$
  $\Rightarrow E_{\mathrm{kin,p}} \sim 1$ GeV: low-energy (quasi)elastic processes.
- Cloud of light quarks and gluons interact with hadronic rate;
  sparticle is inert reservoir of kinetic energy.
- Charge-exchange reactions allowed, e.g.
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{d}\overline{\mathrm{d}}) + \mathrm{p}$.
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way,
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{udd}) + \pi^+$,
  since (a) kinematically disfavoured (π exceptionally light)
  and (b) few pions in matter.

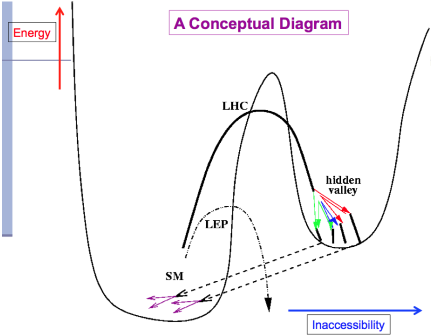
. . . but part of detector simulation (GEANT), not Pythia.

A.C. Kraan, Eur. Phys. J. C37 (2004) 91; M. Fairbairn et al., Phys. Rep. 438 (2007) 1

3. Hidden Valleys: motivation

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .





Courtesy
M. Strassler

L. Carloni & TS, JHEP 1009, 105; L. Carloni, J. Rathsman & TS, JHEP 1104, 091

Hidden Valleys setup

Hidden Valleys (secluded sectors) experimentally interesting if they can give observable consequences at the LHC:

- coupling not-too-weakly to our sector, and
- containing not-too-heavy particles.

Here: no attempt to construct a specific model, but to set up a reasonably generic framework.

Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive γ_v),
2. non-Abelian $SU(N)$, unbroken ($N^2 - 1$ massless g_v's),

with matter q_v's in fundamental representation.

Times three alternative production mechanisms

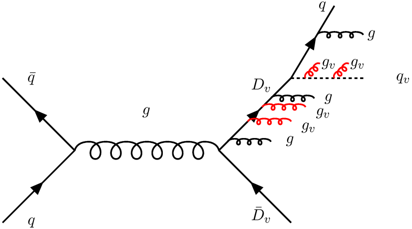
1. massive Z': $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
2. kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
3. massive F_v charged under both SM and hidden group, so e.g. $\mathrm{gg} \to \mathrm{F}_v\overline{\mathrm{F}}_v$. Subsequent decay $\mathrm{F}_v \to \mathrm{f}\mathrm{q}_v$.

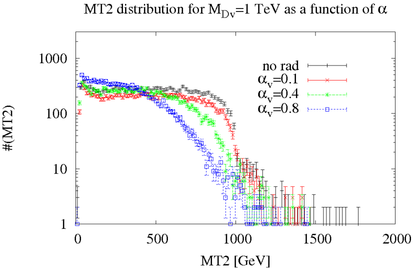
Hidden Valleys showers

Interleaved shower in QCD, QED and HV sectors:
emissions arranged in one common sequence of decreasing emission $p_{\perp}$ scales.

HV $U(1)$: add $\mathrm{q}_v \to \mathrm{q}_v \gamma_v$ and $\mathrm{F}_v \to \mathrm{F}_v \gamma_v$.

HV $SU(N)$: add $\mathrm{q}_v \to \mathrm{q}_v \mathrm{g}_v$, $\mathrm{F}_v \to \mathrm{F}_v \mathrm{g}_v$ and $\mathrm{g}_v \to \mathrm{g}_v \mathrm{g}_v$.





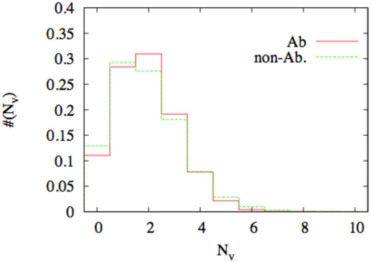
Recoil effects in visible sector also of invisible emissions!

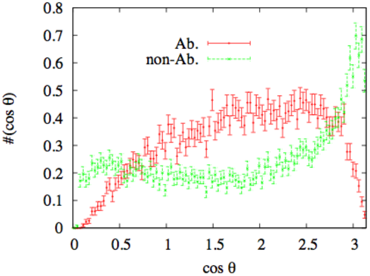
Hidden Valleys decays

Hidden Valley particles may remain invisible, or

- Broken $U(1)$: γ_v acquire mass, radiated γ_vs decay back, $\gamma_v \to \gamma \to \mathrm{f}\overline{\mathrm{f}}$ with BRs as photon ($\Rightarrow$ lepton pairs!)
- $SU(N)$: hadronization in hidden sector, with full string fragmentation setup, giving
  - off-diagonal "mesons", flavour-charged, stable & invisible
  - diagonal "mesons", can decay back $\mathrm{q}_v\overline{\mathrm{q}}_v \to \mathrm{f}\overline{\mathrm{f}}$

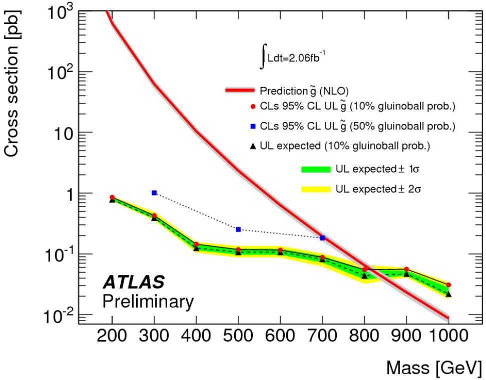
Even when tuned to same average activity, hope to separate

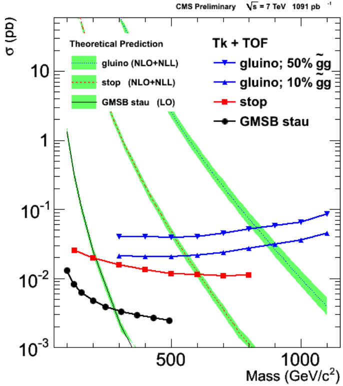




Summary

QCD physics tools can be essential also for BSM searches!

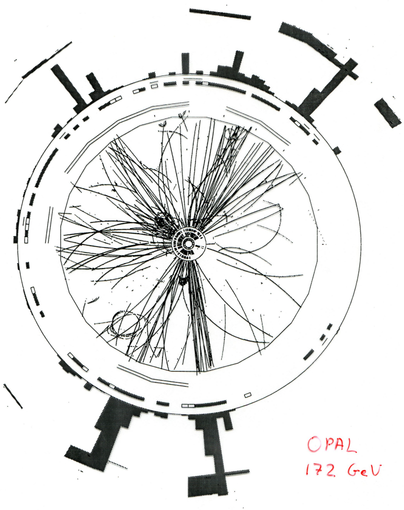




. . . and, hopefully, for upcoming discoveries!

Introduction to Interconnection

$e^+e^- \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\mathrm{q}_3\overline{\mathrm{q}}_4$:



A typical event
contains many partons,
but there are only three colours,
so ambiguities arise.

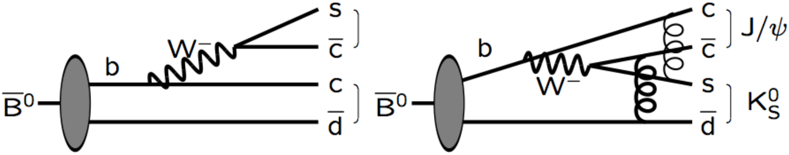
Interconnection =
effects arising when
same-event parton subsystems
can not be viewed as
producing particles independently.

Here:

1. B decays
2. $e^+e^- \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\mathrm{q}_3\overline{\mathrm{q}}_4$
3. Hadronic collisions

Reconnection in B decays

Colour operators in B decay $\Rightarrow$ some η_c:
A. Ali, J.G. Körner, G. Kramer, J. Willrodt, Z. Phys. **C1** (1979) 269

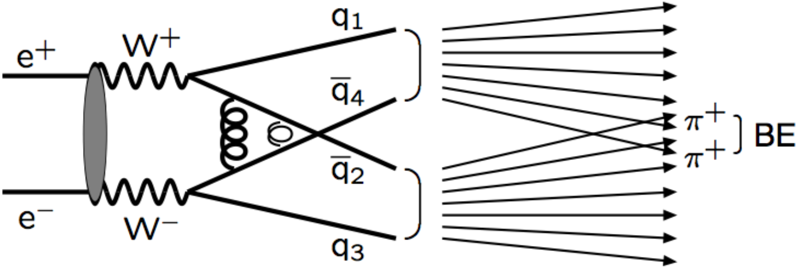


$\mathrm{B} \to \mathrm{J}/\psi \to \mu^+\mu^-$ good way to find B mesons:
H. Fritzsch, Phys. Lett. **B86** (1979) 164, 343
. . . soon confirmed by experiment

$\mathrm{g}^* \to \mathrm{c}\overline{\mathrm{c}} \to \mathrm{J}/\psi$ production mechanism in pp (“colour octet”)
H. Fritzsch, Phys. Lett. **B67** (1977) 217
more complicated to test (at the time, later “confirmed”)

Interconnection at LEP 2

$\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q_1\overline{q}_2\, q_3\overline{q}_4}$ reconnection limits m_{W} precision!



- perturbative $\langle \delta M_{\mathrm{W}} \rangle \lesssim 5$ MeV : negligible!
  (killed by dampening from off-shell W propagators)
- nonperturbative $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV : favoured.
  (but more extreme models from other authors ruled out)
- Bose-Einstein $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV : only little allowed.

V.A. Khoze & TS, PRL 72 (1994) 28;
L. Lönnblad & TS, EPJ C6 (1999) 271

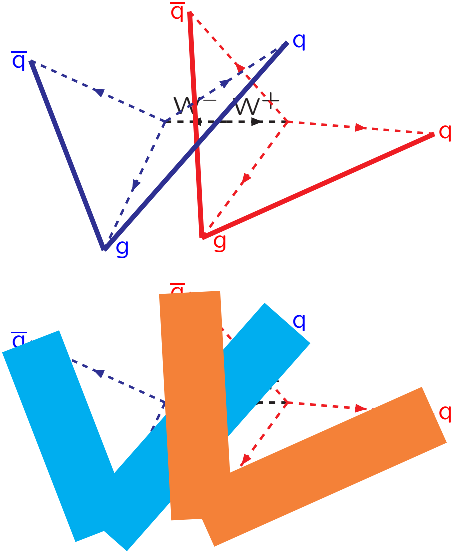
Colour rearrangement models for LEP 2

Colour rearrangement studied in several models, e.g.

Scenario II: vortex lines.
Analogy: type II superconductor.
Strings can reconnect only if central cores cross.

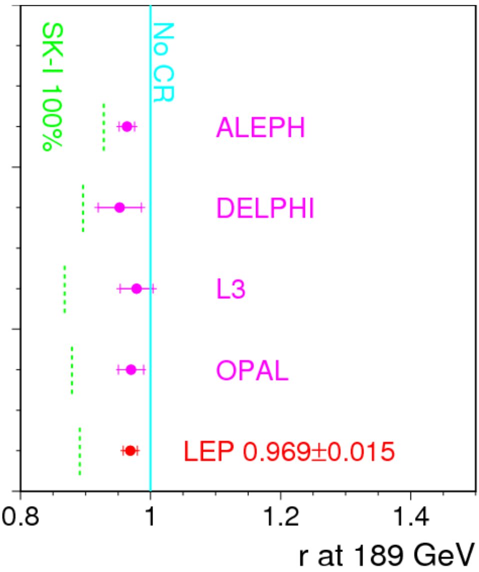
Scenario I: elongated bags.
Analogy: type I superconductor.
Reconnection proportional to space–time overlap.

In both cases favour reconnections that reduce total string length.



(schematic only; nothing to scale)

Colour rearrangement results at LEP 2



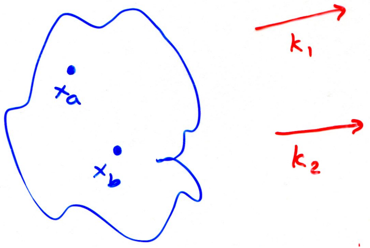
Best LEP2 fit 2013 (topology + mass): 51% of 189 GeV events reconnected in SKI model.

No-CR excluded at 99.5% CL.

Bose–Einstein theory

(Hanbury–Brown, Twiss;
Goldhaber, Goldhaber, Lee, Pais)

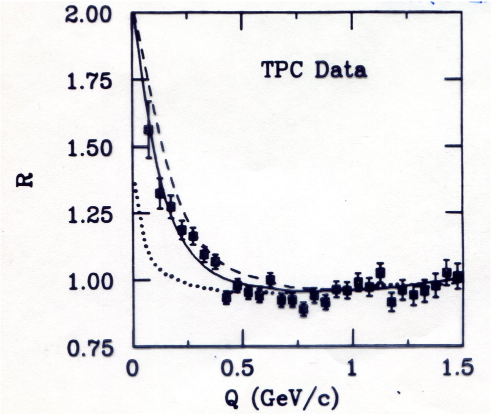
Applies for identical bosons in final state, like $\pi^{\pm}$.
(Fermi–Dirac also observed for identical fermions, like Λ^{+}, but less important.)

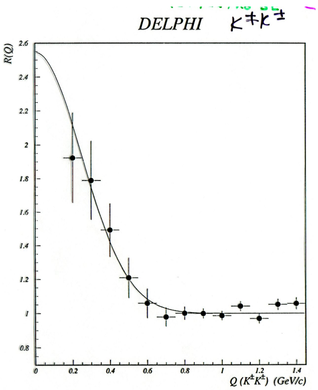


$$
\begin{aligned}
A(1,2) &= \frac{1}{\sqrt{2}} \left\{ e^{ik_1 x_a} e^{ik_2 x_b} + e^{ik_1 x_b} e^{ik_2 x_a} \right\} e^{i\varphi_a} e^{i\varphi_b} \\
P(1,2) &= |A(1,2)|^2 = 1 + \cos(\Delta k \, \Delta x)
\end{aligned}
$$

Assume x_a, x_b distributed according to Gaussian, φ_a, φ_b fluctuate wildly (incoherence), and integrate

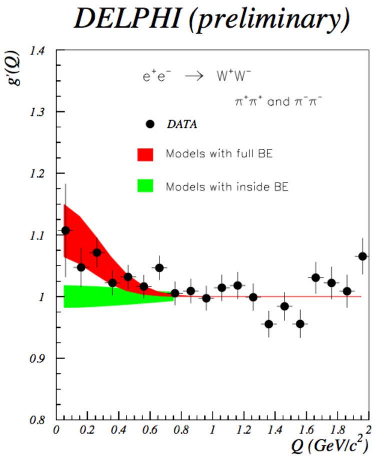
$$
P(1,2) = 1 + \lambda e^{-Q^2 R_0^2} \quad \text{where} \quad Q_{12}^2 = (k_1 - k_2)^2
$$

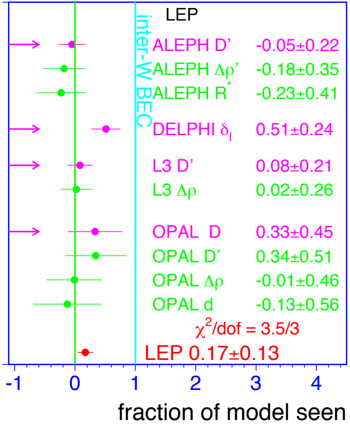




Bose–Einstein well established, but parameters unccertain,
e.g. deformed by resonance decays (most πs produced that way)
$\lambda =$ incoherence parameter ≈ 1
$R =$ source radius $\approx 0.5 - 1$ fm

Bose–Einstein interconnection

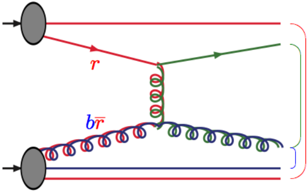


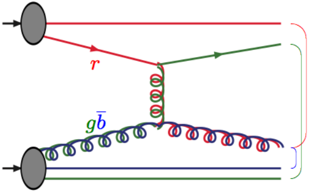


Combined result of 0.17±0.13 of full model effects
⇒ at most 7 MeV effect on W mass.

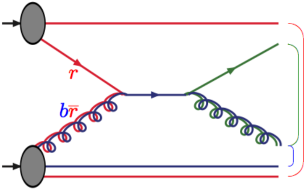
Colour flow in hard processes

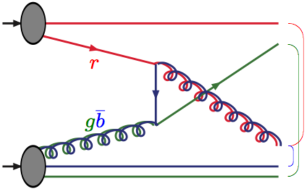
One Feynman graph can correspond to several allowed colour flows, corresponding to different string drawings, e.g. for $\mathrm{qg} \to \mathrm{qg}$:





while other $\mathrm{qg} \to \mathrm{qg}$ graphs only admit one colour flow:

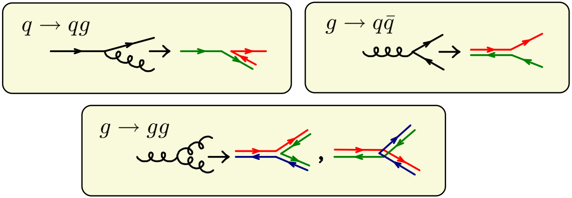




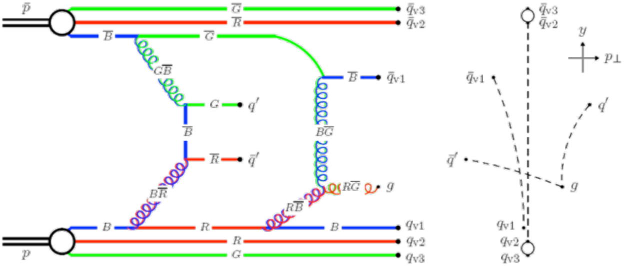
Interference term suppressed $\propto 1/(N_C^2 - 1)$,
so split cross section in proportions given by $N_C \to \infty$ limit.

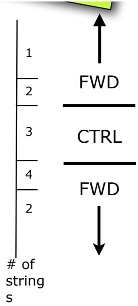
Beam remnants

Also parton showers conveniently traced in $N_C \to \infty$ limit.



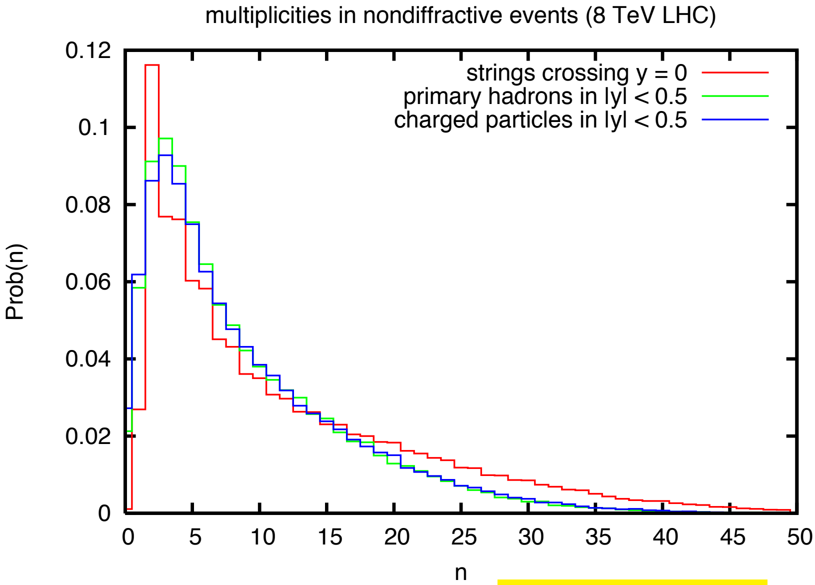
But hooking it all up at beam remnants relies on $N_C = 3$:





Sjöstrand & PS, JHEP 03(2004)053

The Density of particle production



String width $\sim$ hadronic width $\Rightarrow$ Overlap factor $\sim$ 10!

Reconnection at $\mathrm{Sp\bar{p}S}$

T.S. and M. van Zijl,
Phys.Rev. **D36** (1987) 2019

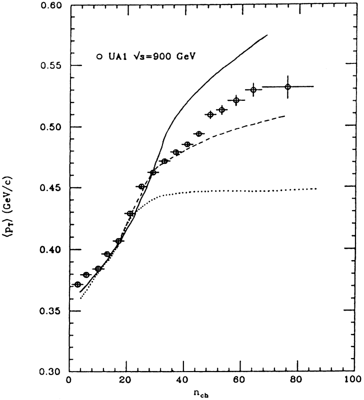
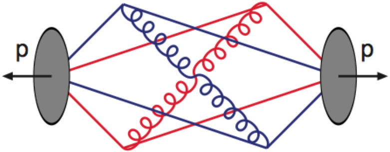
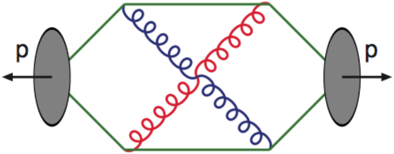


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with "maximal" string length; solid line gg scatterings with "minimal" string length.

$\langle p_\perp \rangle(n_{\mathrm{ch}})$ sensitive to colour flow.



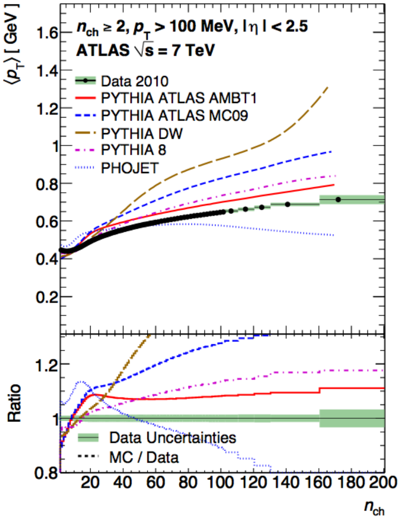
long strings to remnants
$\Rightarrow$ comparable n_{ch}/interaction
$\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ flat.

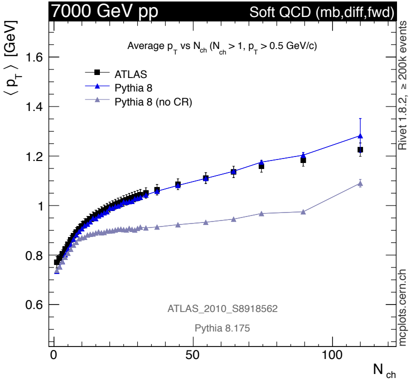


shorter extra strings
for each consecutive interaction
$\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}})$ rising.

Reconnection at the LHC

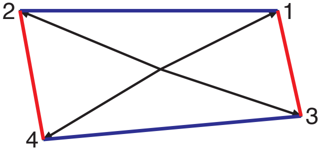
$\langle p_\perp \rangle(n_{\mathrm{ch}})$ effect alive and kicking:





Reconnection important also for other generators, e.g. Herwig++

Colour rearrangement models for the LHC



$m_{13}m_{24} < m_{12}m_{34}$

Space–time models too complicated and uncertain at the LHC
$\Rightarrow$ simplified (in PYTHIA)

Common aspect: reduce string length
$\lambda = \sum \ln(m_{ij}^2/m_0^2) \sim$ multiplicity

Ingelman, Rathsman: reduce $\sum m_{ij}^2$ (Generalized Area Law)

In total 12 scenarios in PYTHIA 6, mainly annealing:

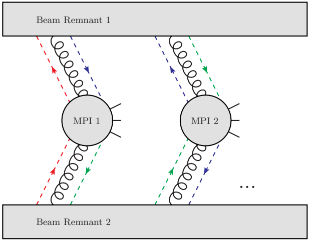
- $P_{\mathrm{reconnect}} = 1 - (1-\chi)^{n_{\mathrm{MPI}}}$ with χ strength parameter.
- Random assignment by $P_{\mathrm{reconnect}}$ for each string piece.
- Choose new combinations that reduce λ (with restrictions).

PYTHIA 8 initially only one model, but more in last year. . .

The new QCD-based beam remnant model (1)

Jesper Christiansen & Peter Skands (in preparation):
new frameworks for beam remnants and colour reconnection;
sharing philosophy, not quite separately available.

- The beam remnant model comes after the perturbative machinery
- Overall idea of the model:
  - A game of conservation laws
  - Add the minimal required amount of extra particles



⋆ Flavour conservation
⋆ Baryon number conservation
⋆ Energy/momentum conservation: modifed PDFs

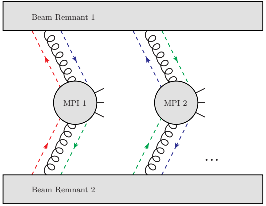
The new QCD-based beam remnant model (2)

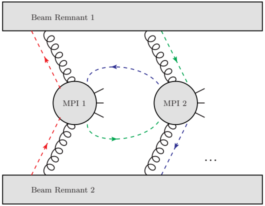
Possible colour states for the two gluons:

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$$

27	$\overline{\mathbf{10}}$	**10**	**8**	**1**
2 C & 2 AC + 1 gluon	0 C & 3 AC + 0 gluon (junction)	3 C & 0 AC + 1 gluon (junction)	1 C & 1 AC + 0 gluon	0 C & 0 AC + 0 gluon (not allowed)

Examples of the **27** and the **8** configurations:

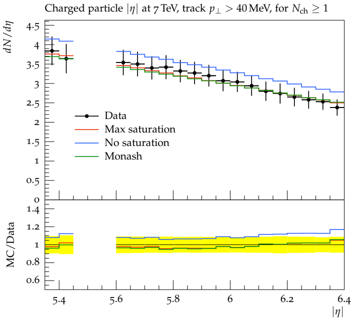




Old model: $\mathbf{8} \otimes \mathbf{8} = \mathbf{8}$, i.e. minimal nonvanishing colour, no junctions in BR (but possible in the event as a whole)

Random walk in colour space unrealistic: partons are correlated.
Included as simple suppression $\exp(-M/k)$,
where M is multiplet size and k is a free parameter

- Relative large x and small $p_\perp \Rightarrow$ forward physics
- Comparison to forward TOTEM measurements.
- 10 % difference between no and maximal saturation
- The old model is similar to maximal saturation



(arXiv:1205.4105)

The new QCD-based CR model (1)

New model relies on two main principles

$\star$ **SU(3)** colour rules give allowed reconnections

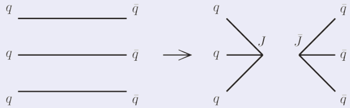
Ordinary string reconnection

($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

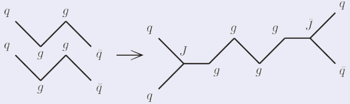
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



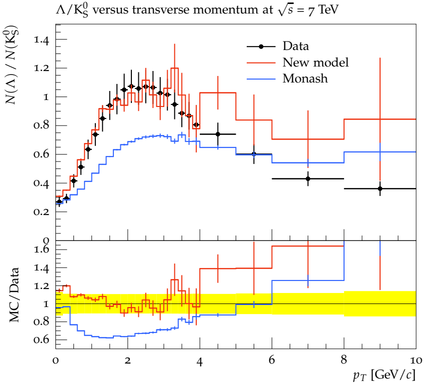
(Depends on number of gluons)

$\star$ minimal λ measure gives preferred reconnections

$\lambda \approx \sum_{\mathrm{dipoles}} \ln(1 + m_{ij}^2/m_0^2)$ measure of string length, $\propto n_{\mathrm{hadronic}}$

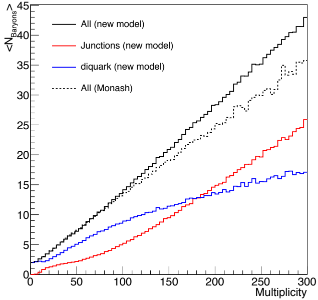
The new QCD-based CR model (2)

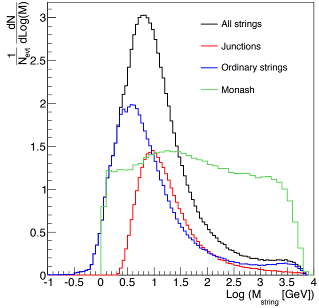
Comparison with LHC data:



(arXiv:1102.4282)

many baryons from junctions,
but few from regular strings
(big-mass string systems cut up!)

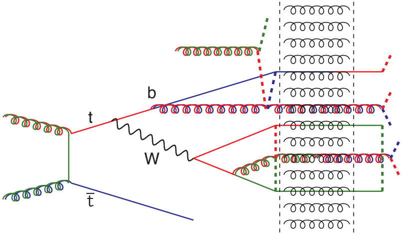




A top mass puzzle

$$\left.\begin{array}{l}\Gamma_{\mathrm{t}} \approx 1.5\ \mathrm{GeV} \\ \Gamma_{\mathrm{W}} \approx 2\ \mathrm{GeV} \\ \Gamma_{\mathrm{Z}} \approx 2.5\ \mathrm{GeV}\end{array}\right\} \Rightarrow c\tau \approx 0.1\ \mathrm{fm}:$$

p "pancakes" have passed,
MPI/ISR/FSR for $p_{\perp} \geq 2$ GeV,
inside hadronization colour fields.



Experiment	m_{top} [GeV]	Error due to CR	Reference
World comb.	173.34±0.76	310 MeV (**40%**)	arXiv:1403.4427
CMS	172.22±0.73	150 MeV (**20%**)	CMS-PAS-TOP-14-001
D0	174.98±0.76	100 MeV (**13%**)	arXiv:1405.1756

(S. Argyropoulos)

1. Great job in reducing the errors.
2. CR is one of the dominant systematics.
3. Why is the CR uncertainty going down when there are
   - no advances in theoretical understanding, and
   - no measurements to constrain it?

Top mass shift in PYTHIA 6

Studies for the Tevatron.

Green bands: old virtuality-ordered showers.

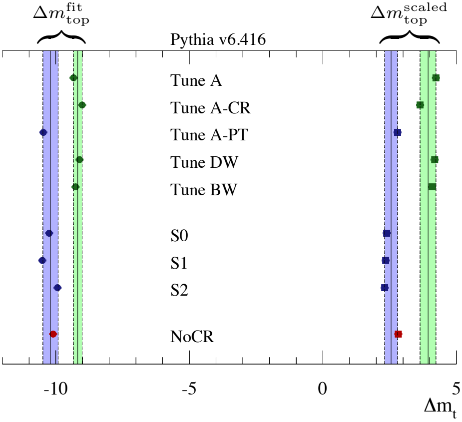
Blue bands: new $p_\perp$-ordered showers.

In total ± 1.0 GeV,

whereof ± 0.7 GeV perturbative,

and ± 0.5 GeV nonperturbative.

Fit $\rightarrow$ scaled: Jet Energy Scaling.



(M.Sandhoff and P.Z Skands, FERMILAB-CONF-05-518-T;)
D. Wicke and P.Z. Skands, EPJ C52 (2007) 133, Nuovo Cim. B123 (2008) S1

New Pythia 8.2 CR models

PYTHIA 8.1: one CR model, joining some MPIs, with reduced λ.
Late/early resonance decays: after/before CR.

S. Argyropoulos & TS: JHEP 11 (2014) 043

Basic idea: produce range of models to study how big Δm_{top} could be without contradicting data.

Top CR as afterburner:
toy / **stealth** models

- forced random
- forced nearest
- forced farthest
- forced smallest $\Delta\lambda$
- smallest $\Delta\lambda$

only for top

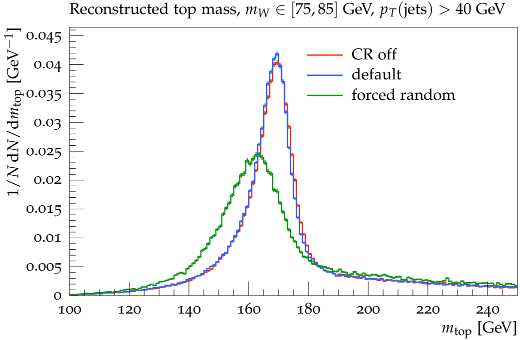
Top CR on equal footing:
more sophisticated / fragile

- swap
- move
- swap + flip
- move + flip

so as to reduce λ

also for MB/UE

Effects on top mass before tuning



Δm_{top} relative to no CR:

model	Δm_{top} [GeV]	Δm_{top} rescaled
default (late)	-0.415	$+0.209$
default early	$+0.381$	$+0.285$
forced random	-6.970	-6.508

Asymmetric spread:
$\Delta m_{\mathrm{top}} < 0$ easy,
$\Delta m_{\mathrm{top}} > 0$ difficult.

Parton showers already prefer minimal λ.

Main effect from jet broadening, some from jet–jet angles.

Effects on top mass after tuning

No publicly available measurements of UE in top events.

- Afterburner models tuned to ATLAS jet shapes in $\mathrm{t}\bar{\mathrm{t}}$ events
  $\Rightarrow$ high CR strengths disfavoured.
- Early-decay models tuned to ATLAS minimum bias data
  $\Rightarrow$ maximal CR strengths required to (almost) match $\langle p_\perp \rangle(n_{\mathrm{ch}})$.

model	Δm_{top} rescaled
default (late)	$+0.239$
forced random	-0.524
swap	$+0.273$

Δm_{top} relative to no CR

Excluding most extreme (unrealistic) models

$$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.50}\ \text{GeV}$$

(in line with Sandhoff, Skands & Wicke)

New: $\Delta m_{\mathrm{top}} \approx 0$ in QCD-based model

Studies of top events could help constrain models:

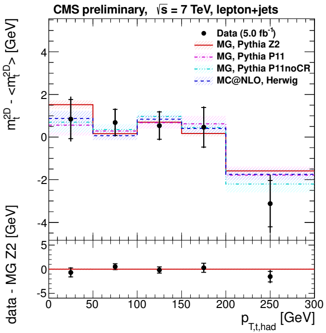
- jet profiles and jet pull (skewness)
- underlying event

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

NEW

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



- *First top mass measurement binned in kinematic observables.*
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS~ masses.

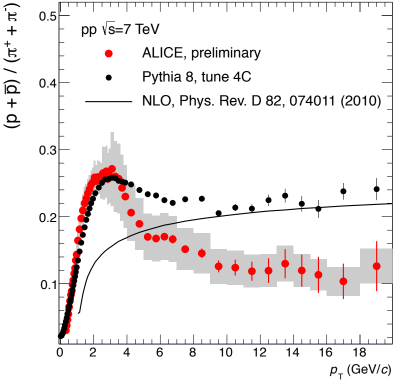
E. Yazgan

(Moriond 2013)

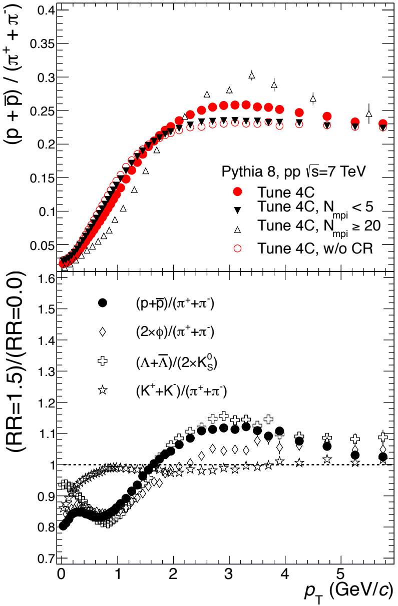
1(

Reconnection and collective flow

Transverse boosts $\Rightarrow$
$\sim$ collective particle vecocity.
More common with reconnection.

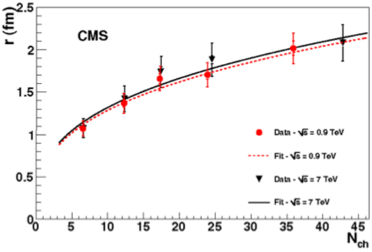


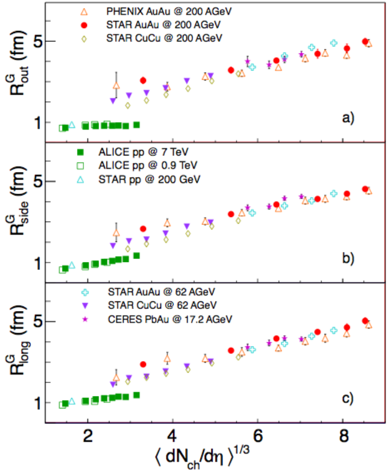
A. Ortiz Velasquez et al.,
Phys. Rev. Lett. 111 (2013) 042001



Bose–Einstein at the LHC (1)

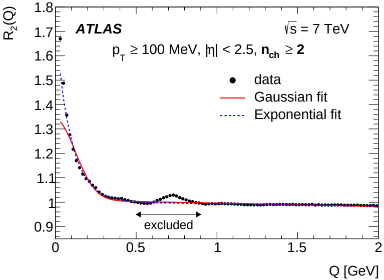
Bose-Einstein $r(N_{\text{ch}}) \propto N_{\text{ch}}^{1/3}$
cannot be accommodated
in PYTHIA effective description
that worked at LEP





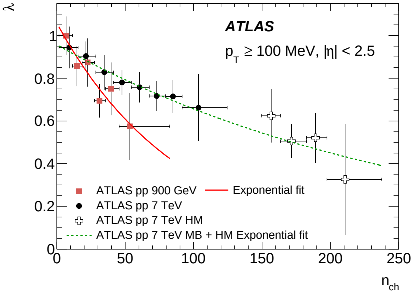
Multiple overlapping fragmenting strings ⇒ dense hadron gas!

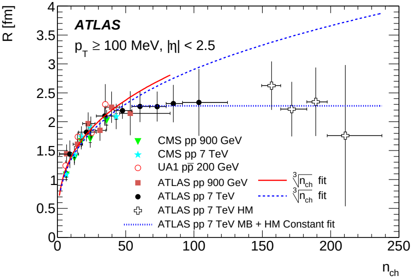
Bose–Einstein at the LHC (2)



Exponential $1 + \lambda \exp(-RQ)$ OK;
Gaussian $1 + \lambda \exp(-R^2 Q^2)$ not.

Inclusively 7 TeV:
$\lambda = 0.71 \pm 0.07$
$R = 2.06 \pm 0.22$ fm
(cf. LEP ~ 0.7 fm)





The Road Ahead – Generators

Many obvious evolutionary steps:

- automated NLO $\Rightarrow$ MC@NLO &POWHEG calculations
- improved matching&merging algorithms with NLO MEs
- parton showers with complete NLL accuracy
- improved MPI and hadronization frameworks

And some revolutionary ones:

- automated multiloops for complete N^{n}LO calculations, e.g. ficititious gluon mass avoiding divergences and dimensional regularization
- lattice QCD explains how strings break and what happens when hadrons are closely packed

What is progress (in the eyes of experimentalists)?

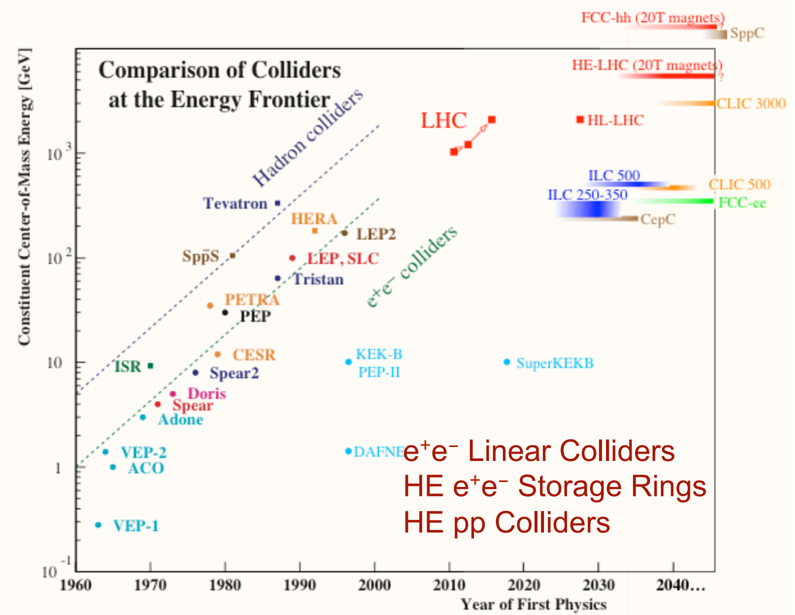
- more complicated models with more tunable parameters, giving better agreement with data?
- more sophisticated/predictive models with fewer tunable parameters, giving *worse* agreement with data?

Future Colliders

Many proposals

- SuperKEKB – Belle II (Japan) $40 \times \mathcal{L} = 8 \cdot 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- LHC luminosity upgrade
- ILC – International Linear Collider (Japan)
- CepC/SPPC (China)
- 33 TeV LHC (now fallback?)
- FCC – Future Circular Collider
  - $\mathrm{e}^+\mathrm{e}^-$
  - pp
  - ep (?? recall that ep was part of LHC program)
- CLIC – Compact LInear Collider
- Muon collider
- (Neutrino beams)
- (Cosmic rays)
- (Dark matter searches)

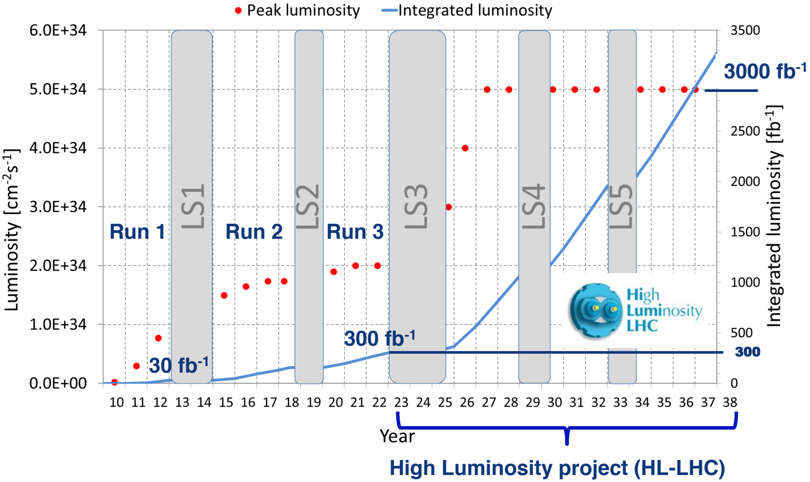
Livingston plot (Nick Walker)



e+e− Linear Colliders
HE e+e− Storage Rings
HE pp Colliders

LHC luminosity upgrade

LHC roadmap: **Goal of 3'000 fb^{-1}** by mid 2030ies

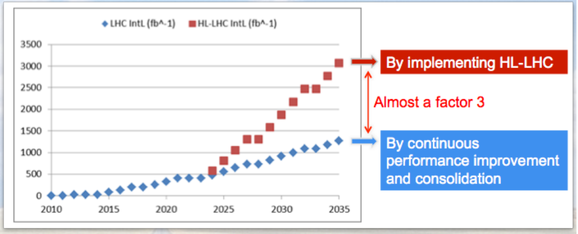


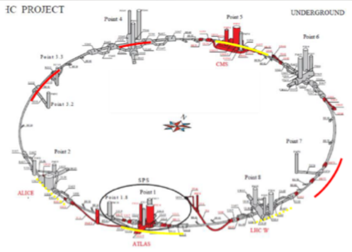
High Luminosity LHC

"Full exploitation of LHC project with HL-LHC is mandatory"

European Strategy: European top priority

P5: US highest-priority near-term large project

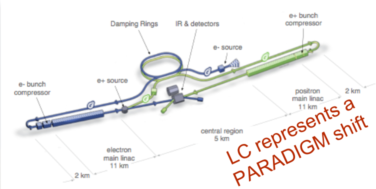




- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention >1.2 km of LHC complex

INTERNATIONAL LINEAR COLLIDER



- **200-500 GeV cm (extendable to 1 TeV)**
  - L ~ 1.8×10^{34} cm^{-2}s^{-1} (@ 500GeV)
  - 7.8 Billion ILCU + 23 Million p-hrs
- **>20 years R&D worldwide**
  - A truly global effort
  - Over 2,000 man years
  - >300 M$ globally

- **Cost driver: SRF technology**
  - 17,000 1.3 GHz Nb cavities
  - 1,800 cryomodules
- **Mature SRF technology**

International Linear Collider – 2 (Nick Walker)

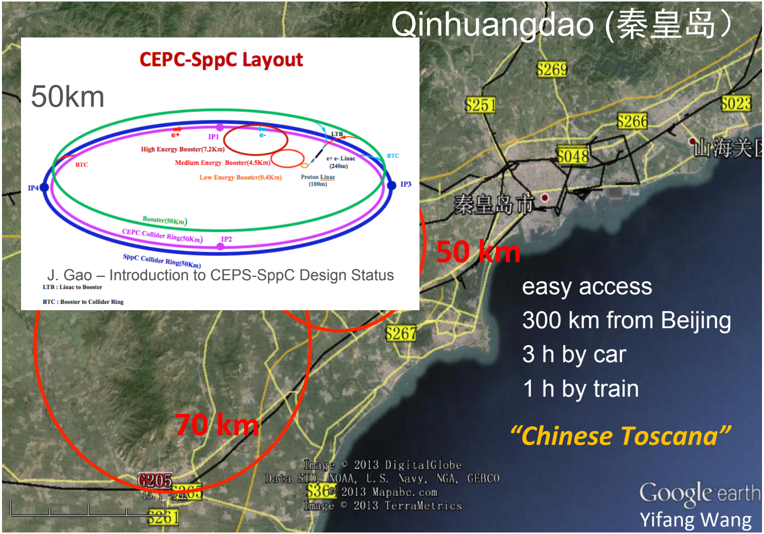
Only new machine “ready to go” — if the political will is there.

Formal Japanese invitation to the world in 2013.

2018: possible construction start.

2028: possible date for first physics.

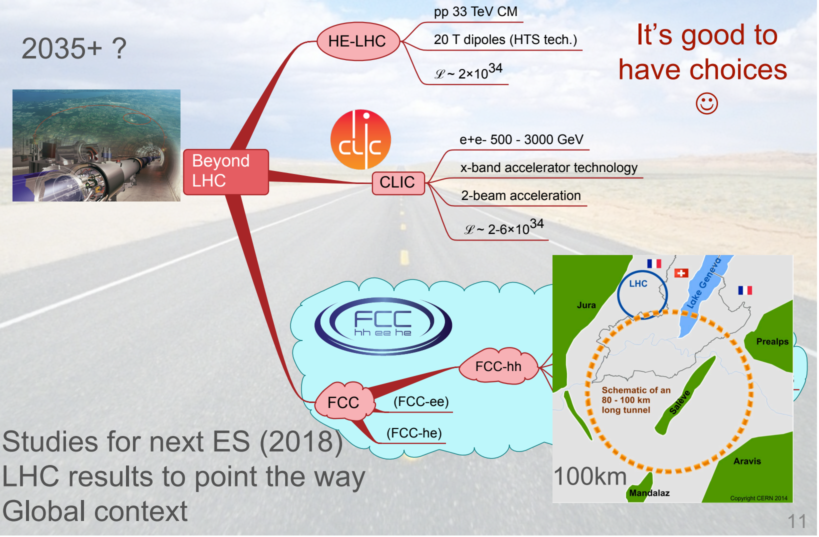
Chinese CepC/SppC (Nick Walker)



CepC Conceptual Design Report in 2014.

e^+e^- collisions in $\sim$ 2028; pp collisions in $\sim$ 2042.

CERN Future (Nick Walker)

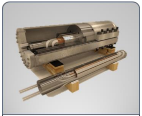


Goal of FCC study is a Conceptual Design Report by end of 2018, in time for next European Strategy Update

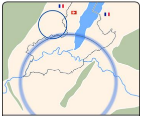
Scope: Accelerator & Infrastructure

Collider Designs

FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions

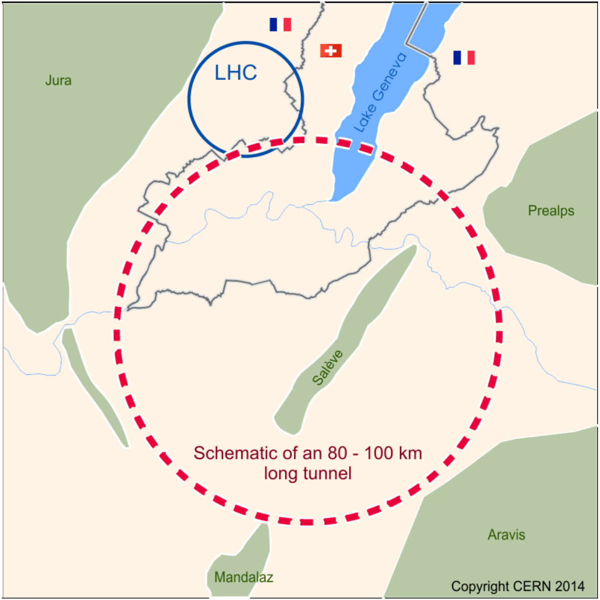

R&D Programs

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources


Infrastructures

Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

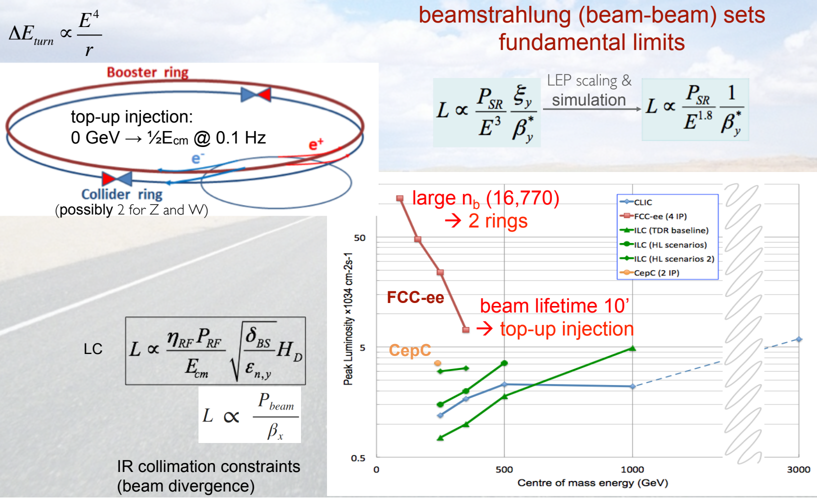
FCC layout



Currently 93 km circumference preferred geologically

FCC $e^{+}e^{-}$ parameters

Version 2.0 (2014-09-05)	LEP2	FCC-ee Z	FCC-ee W	FCC-ee H	FCC-ee tt
Circumference [km]	26.7	**100**			
Bending radius [km]	3.1	**11**			
Beam energy [GeV]	104	**45.5**	**80**	**120**	**175**
Beam current [mA]	3.04	**1450**	**152**	**30**	**6.6**
Bunches / beam	4	16700	4490	1360	98
Bunch population [10^{11}]	4.2	1.8	0.7	0.46	1.4
Beam size at IP s* [mm]					
- Horizontal	182	121	41	22	45
- Vertical	3.2	0.25	0.084	0.044	0.045
Energy loss / turn [GeV]	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	11	**50**			
Total RF voltage [GV]	3.5	**2.5**	**4**	**5.5**	**11**
RF frequency [MHz]	352	**800**			
Luminosity / IP [10^{34} cm^{-2}s^{-1}]	0.012	**28.0**	**12.0**	**6.0**	**1.8**
Luminosity lifetime [min][(1)]	434	298	73	29	21

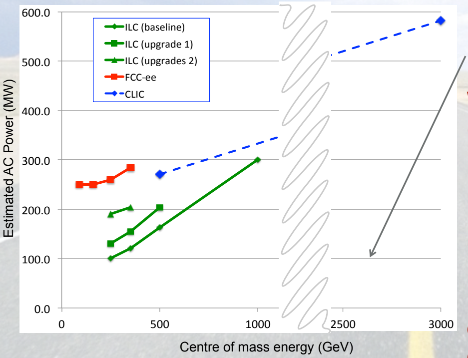


$\Delta E_{turn} \propto \frac{E^4}{r}$
beamstrahlung (beam-beam) sets fundamental limits
Booster ring
top-up injection:
0 GeV → ½E_{cm} @ 0.1 Hz
e^+
e^-
Collider ring
(possibly 2 for Z and W)
$L \propto \frac{P_{SR}}{E^3}\frac{\xi_y}{\beta_y^*}$
LEP scaling & simulation
$L \propto \frac{P_{SR}}{E^{1.8}}\frac{1}{\beta_y^*}$
LC
$L \propto \frac{\eta_{RF}P_{RF}}{E_{cm}}\sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}}H_D$
$L \propto \frac{P_{beam}}{\beta_x}$
IR collimation constraints
(beam divergence)
large n_b (16,770)
→ 2 rings
FCC-ee
CepC
beam lifetime 10'
→ top-up injection
CLIC
FCC-ee (4 IP)
ILC (TDR baseline)
ILC (HL scenarios)
ILC (HL scenarios 2)
CepC (2 IP)
Peak Luminosity ×1034 cm-2s-1
50
5
0.5
0
500
1000
3000
Centre of mass energy (GeV)

e^+e^- power requirements (Nick Walker)

$\mathscr{L} \times E_{\mathrm{CM}} \rightarrow$ MWatt

at least for lepton machines



LHC machine <100 MW

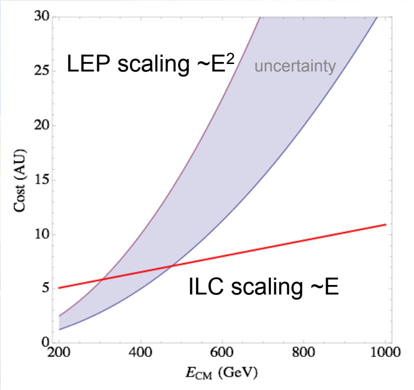
Where are the acceptable limits? (not the technical limits)

High running costs may need to be shared (*global* project)

R&D needed in increasing efficiencies and/or recovering the energy

e^+e^- scaling (Nick Walker)

Storage rings or linear colliders?



Note: over simplified. Need to wait for robust and defendable cost estimates from storage ring studies

- Cost scaling (and length)
  - Already identified 50 year ago
- 250 GeV favours storage ring
- 350-500 GeV and up: linear collider starts to look better
  - above 500 GeV likely only option
- Physics, cost (and *opportunity*!) must decide!
- **The ultimate future of e^+e^- colliders is linear**
  - **or not at all**

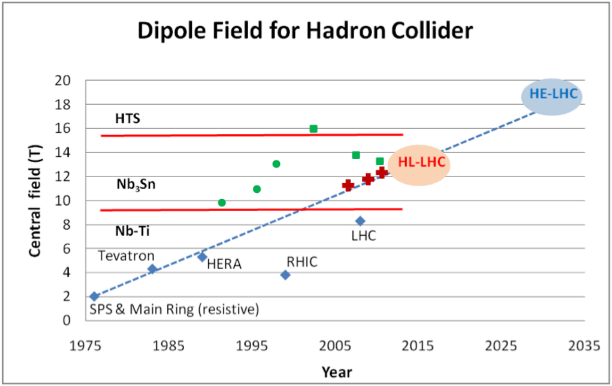
LC represents a PARADIGM shift

FCC pp parameters

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference C [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Arc filling factor	0.79		0.79	0.79
Straight sections	8		8	12
Average straight section length [m]	528		528	1400
Number of IPs				2 + 2
Injection energy [TeV]	0.45		> 1.0	3.3
Physics performance and beam parameters				
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	 27	 135 (lev.)	 147	 171 34
Total / inelastic cross section σ_{proton} [mbarn]	111 / 85		129 / 93	153 / 108

HE-LHC & FCC pp magnets (Nick Walker)

Is it really possibile to go so high?

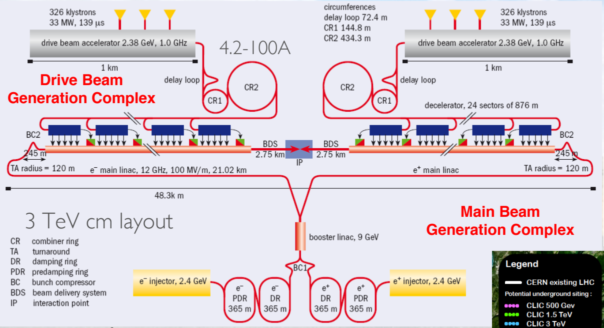


Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. Such a challenge is similar to a 40 T solenoid (μ-C)

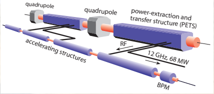
◆ Nb-Ti operating dipoles; ● Nb3Sn cosϑ test dipoles ■ Nb3Sn block test dipoles ✚ Nb3Sn cosϑ LARP QUADs

courtesy: L. Rossi (CERN)

Compact (or CERN) LInear Collider (Nick Walker)

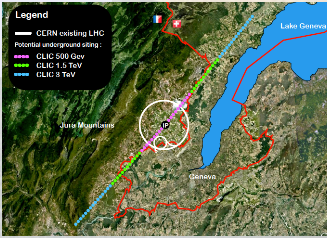


$G_a \sim 100$ MV/m



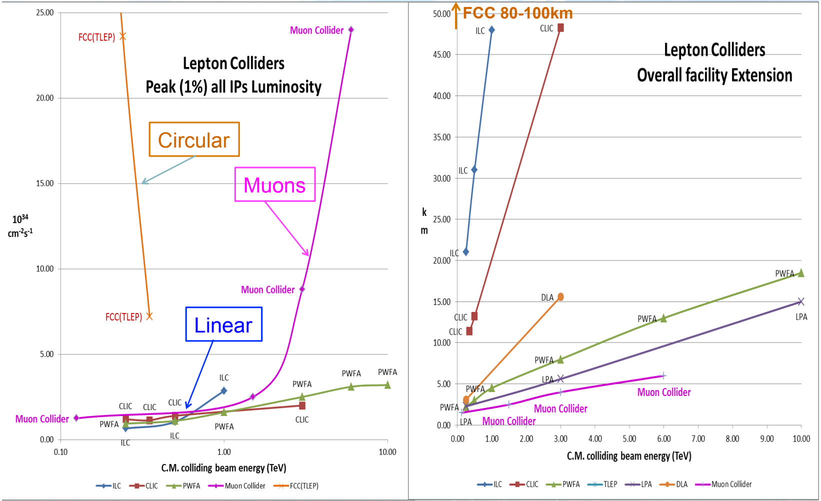
LC represents a PARADIGM shift

CLIC
- e+e- 500 - 3000 GeV
- x-band accelerator technology
- 2-beam acceleration
- $\mathscr{L} \sim 2\text{-}6 \times 10^{34}$



0.5 TeV: 8,300 MCHF ($\mathscr{L} \sim 1.4 \times 10^{34}$)

Muon Colliders extending high energy frontier [with potential of considerable cost savings]



Courtesy J.P.Delahaye, IPAC14

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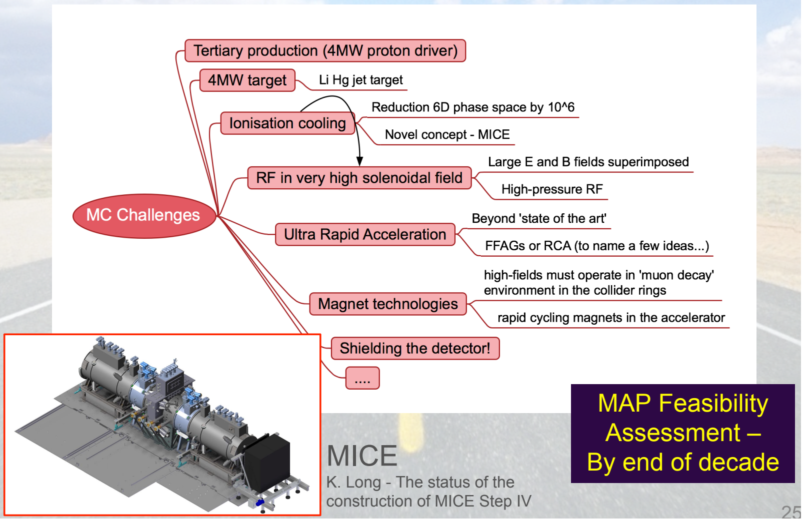
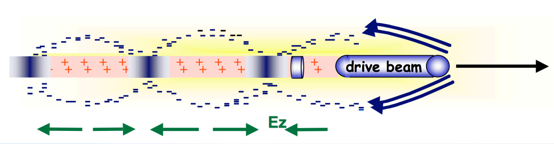
Muon Colliders – 2 (Nick Walker)



On the up side:

a 6 TeV muon collider comfortably fits on the Fermilab site!

The dream of GV per cm



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

	n_0	E_0	λ_p
Laser-driven	10^{17} cm^{-3}	30 GV/m	100 μm
e/p-driven	10^{18} cm^{-3}	100 GV/m	30 μm

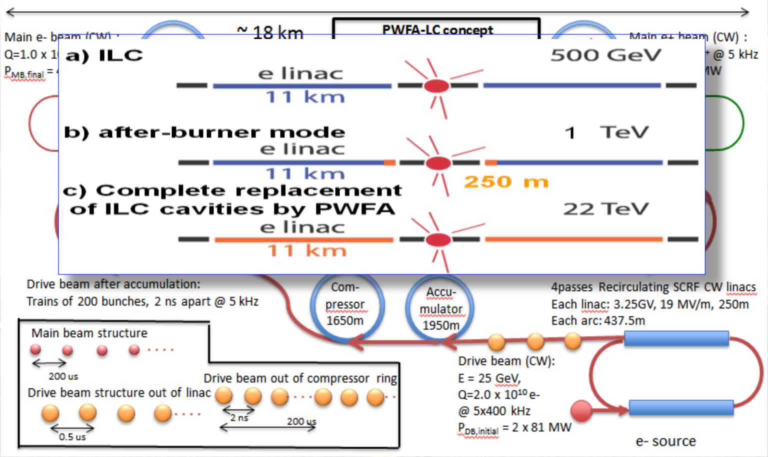
light sources

HEP?

Fundamental “blue skies” research

- understanding / demonstrating the acceleration process
- benchmarking computer simulation models
- Experiments: AWAKE [CERN], FACET & FACET 2 [SLAC], FLASH*forward* [DESY]

Dream the dream: PWA Linear Collider



ILC “upgrade” - 1 GeV/m → 10 TeV. L~10^{35} P_{AC} ~500 MW

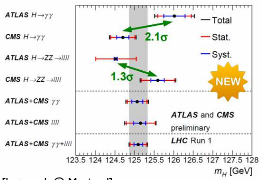
$$V(h) = -m^2 h^\dagger h$$

c. March 2015:
Barely scratched
the surface

$$\mathcal{L} \supset y_\psi \psi h \psi^c$$

Key FCC-ee/hh/he Targets

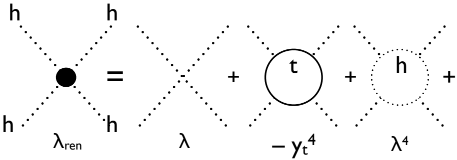
$+\lambda_h (h^\dagger h)^2$	$+\ \|h\|^6$?	$+\ V(h_2, s, \ldots)$?
Higgs self-coupling	Higgs compositeness	extended Higgs sectors
$\times\ \|h\|^2$?	$+\ \|h^\dagger D_\mu h\|^2$?	$+\ \|h\|^2 O_{BSM}$?
mass/coupling relations	precision electroweak	Higgs portal to new physics



[last week @ Moriond]

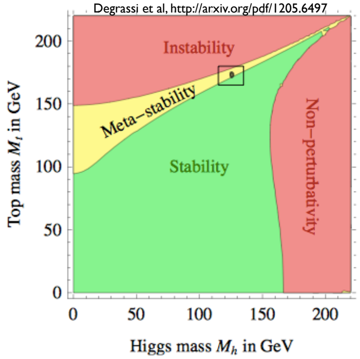
& electroweak phase transition,
new physics in loops, neutral naturaleness, …

Higgs physics alone worth investment in FCC



$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$



Higgs selfcoupling and coupling to the top are the key inputs to assess the stability of the Higgs potential

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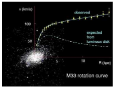
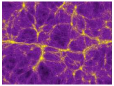
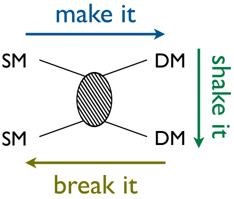
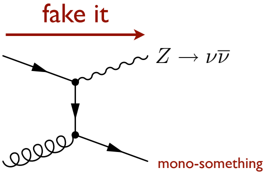
Dark Matter





WIMP Paradigm?

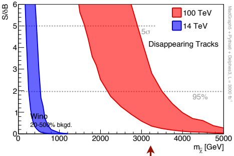




e.g. Pure Wino-like DM
(electroweak triplet):

$\chi^\pm$
χ^0 $\gtrsim \Delta m \approx m_{\pi+}$

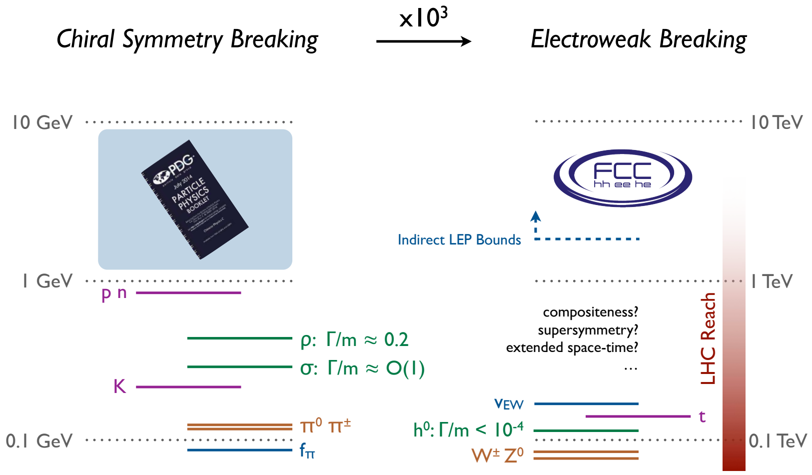
Disappearing Tracks



Thermal Relic Expectation
(non-thermal/partial DM equally plausible)

[Low, Wang, 2014]

Hierarchy Problem (Jesse Thaler)



Measurements ⇔ *Core Principles of SM*

W Polarization in Top Decay ⇔ *Spontaneous Electroweak Breaking*

Higgs Pair Production ⇔ *Nature of Higgs Potential*

High Mass Drell-Yan ⇔ *Electroweak Coupling Running*

Higgs Event Shapes ⇔ *Quark/Gluon Color Scaling*

Neutrino Jets ⇔ *Electroweak Radiation*

Soft Drop Grooming ⇔ *QCD Splitting Functions*

... ⇔ ...

Non-trivial, intrinsically interesting
Deviations are sure signs of new physics