p-p Physics at LHC

Hard scattering. Underlying event. Pile Up

Lecture 2

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Fisica delle Particelle Elementari, Anno Accademico 2015-16

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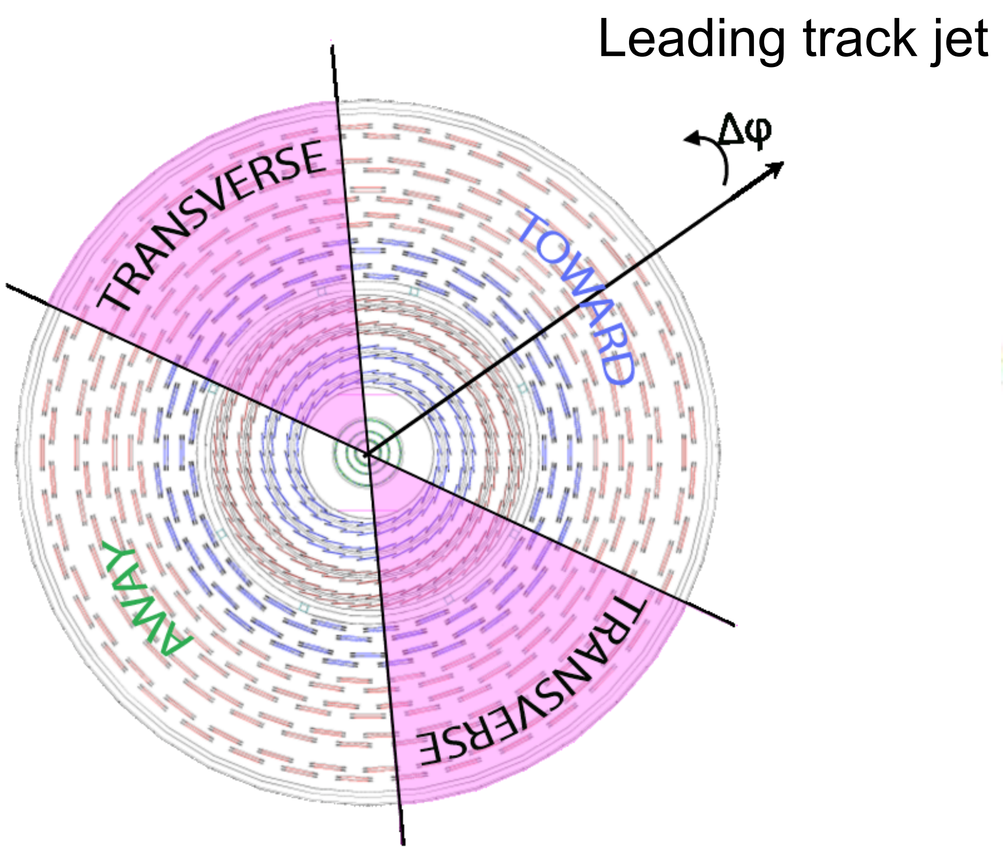
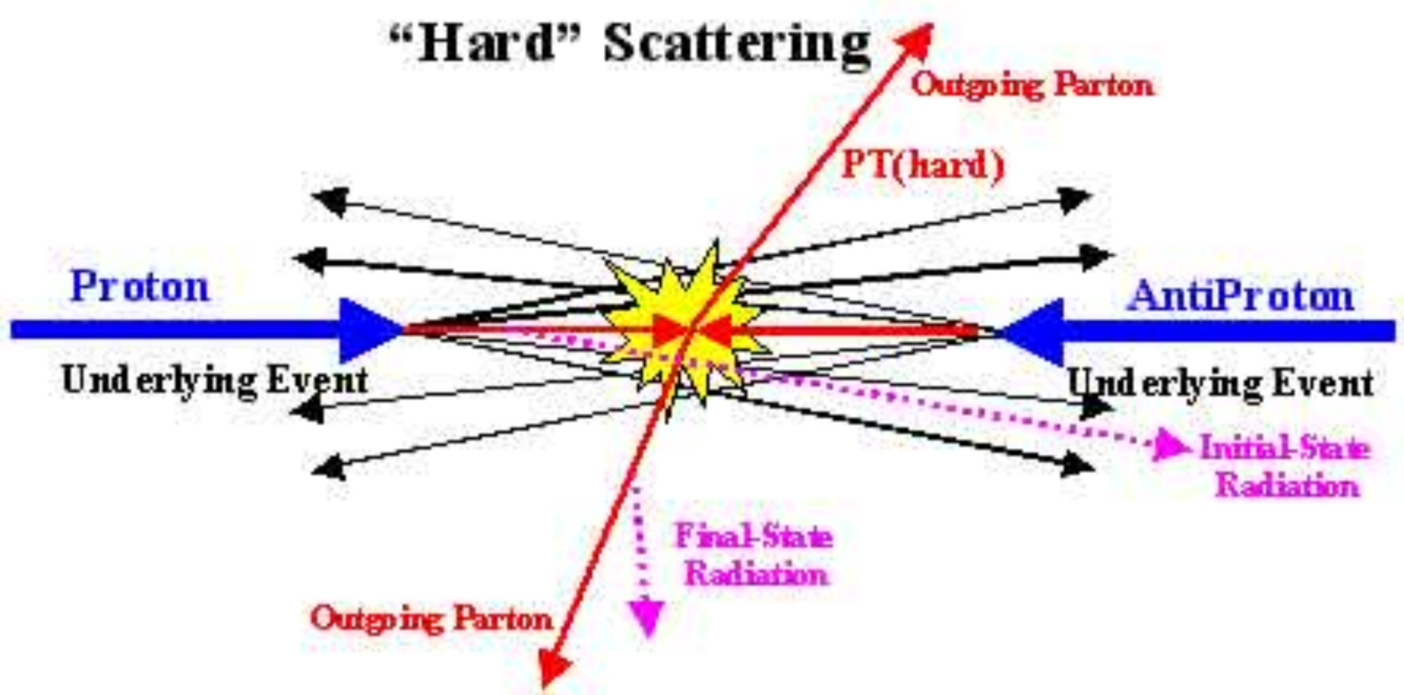
UNDERLYING EVENT

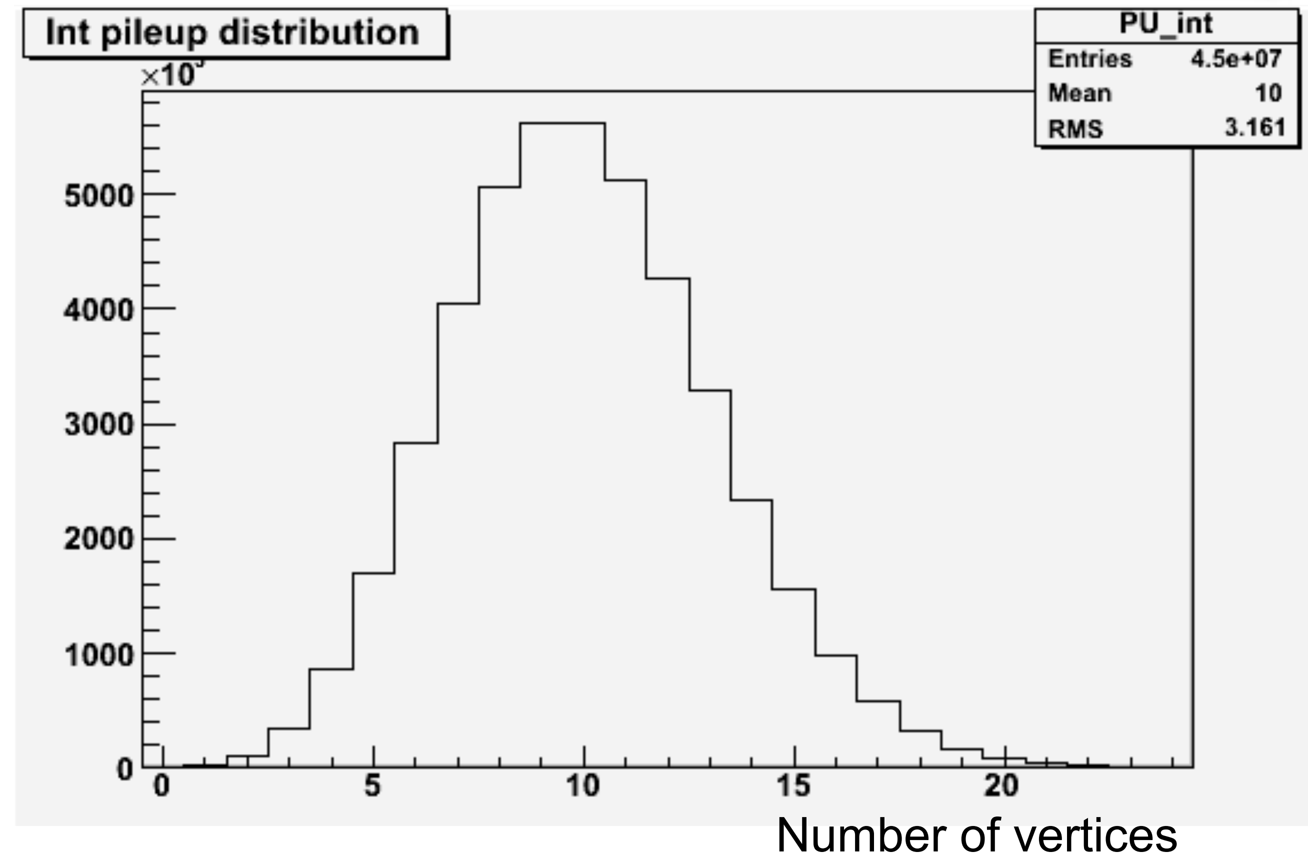


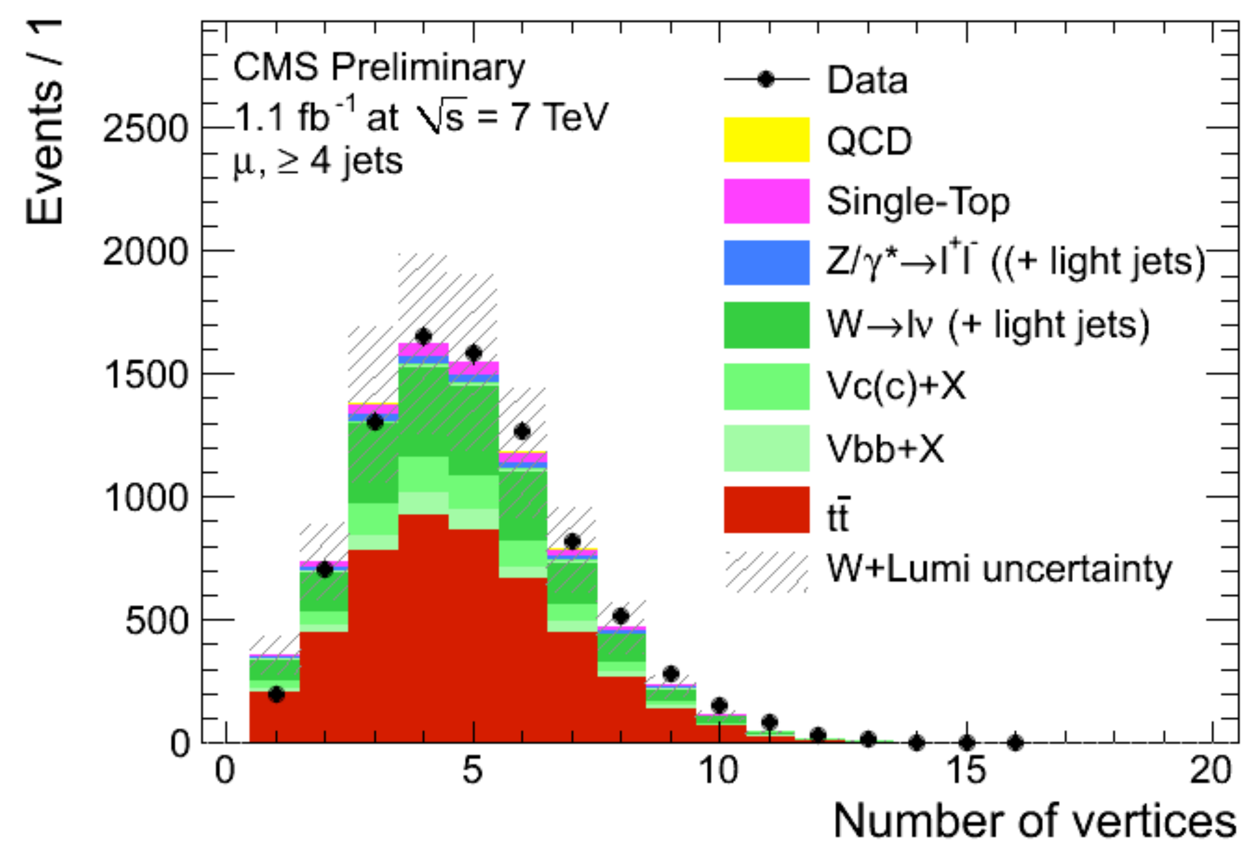


- Jet reconstruction with only charged tracks
- Use leading jet (jet with highest pt in the event) to define forward direction
- Study activity in 4 different regions

PILE-UP

- High probability of more than 1 proton-pair interaction with
    - smaller beam section
    - higher number of protons per bunch
- Typically one interesting hard-scattering of interest
    - the "event" causing the trigger
- Additional collisions in same bunch crossing increase average energy density in detectors
    - higher occupancy
    - distortion or mis-measurement of energy in calorimeters
    - Potential inefficiency in track reconstruction in very busy events
- Much larger event processing time

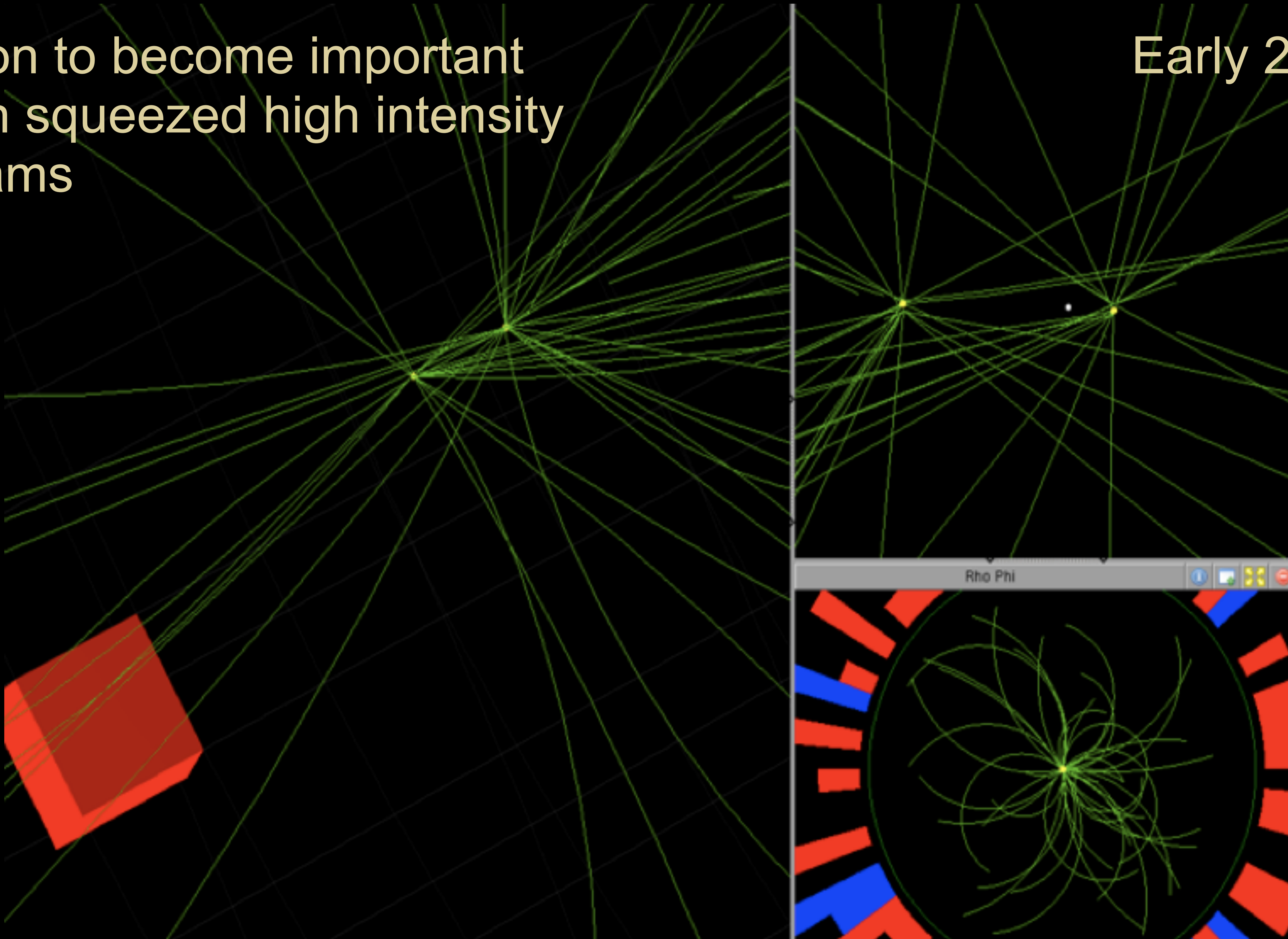




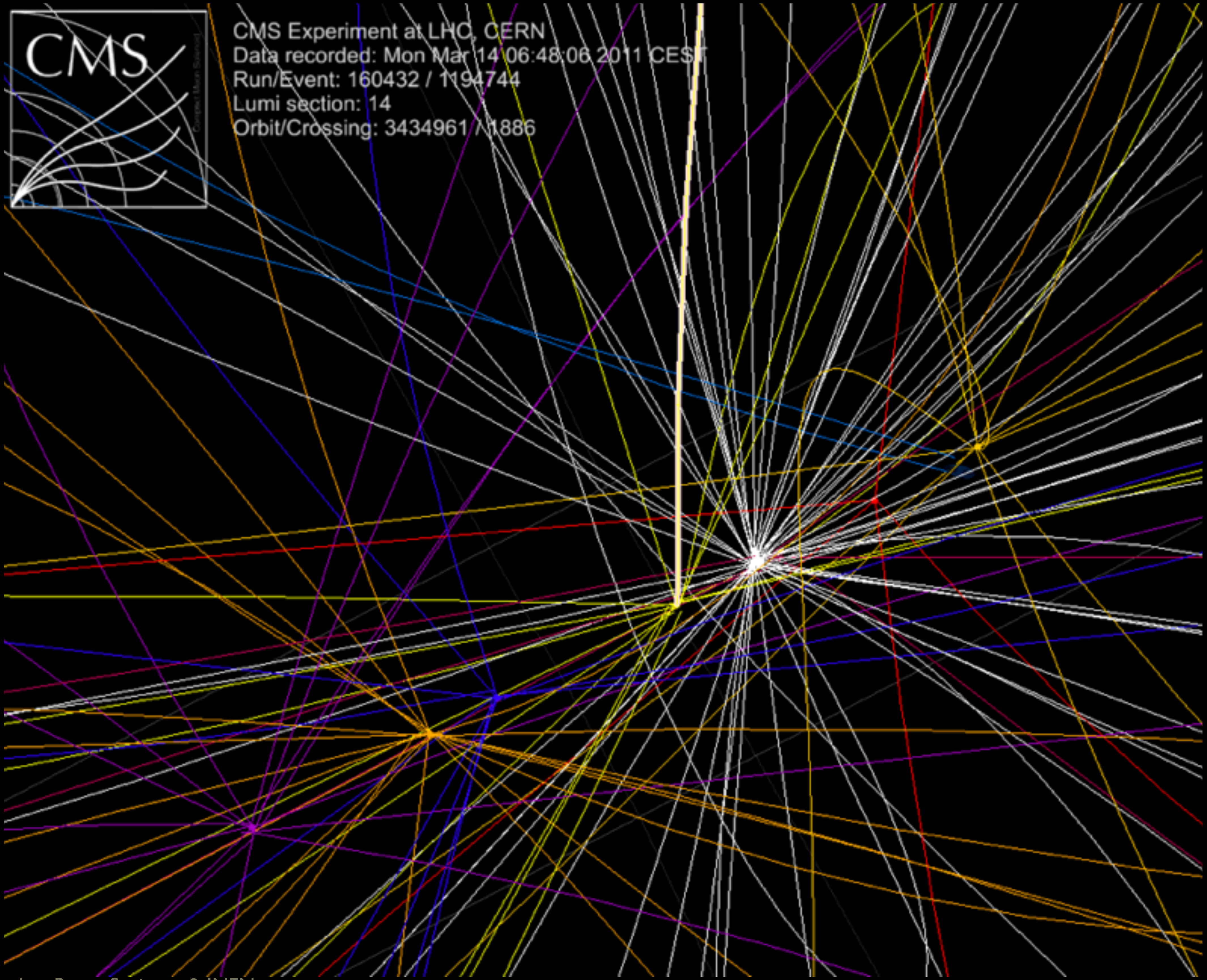
Pile-Up at Low Luminosity

Soon to become important with squeezed high intensity beams

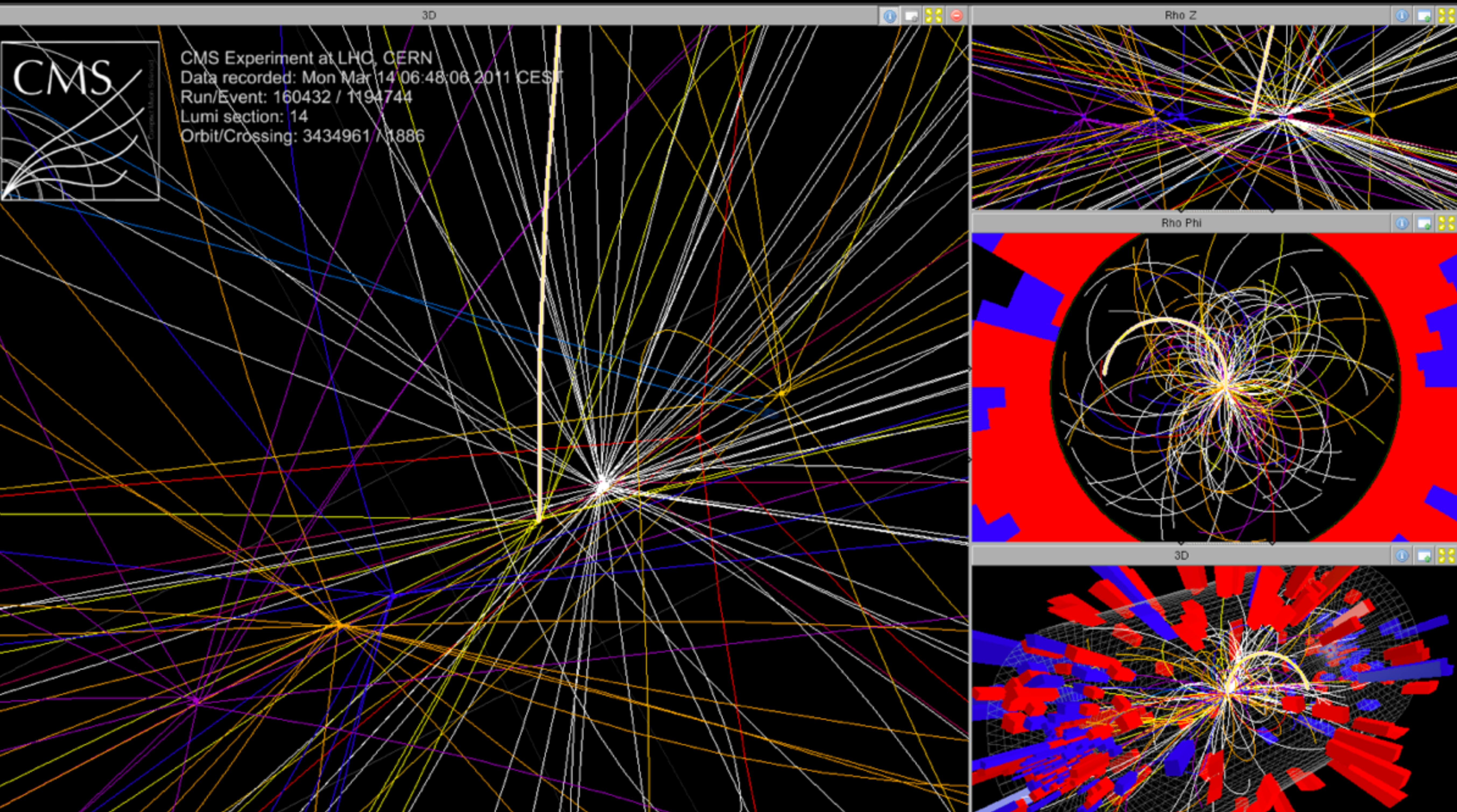
Early 2010



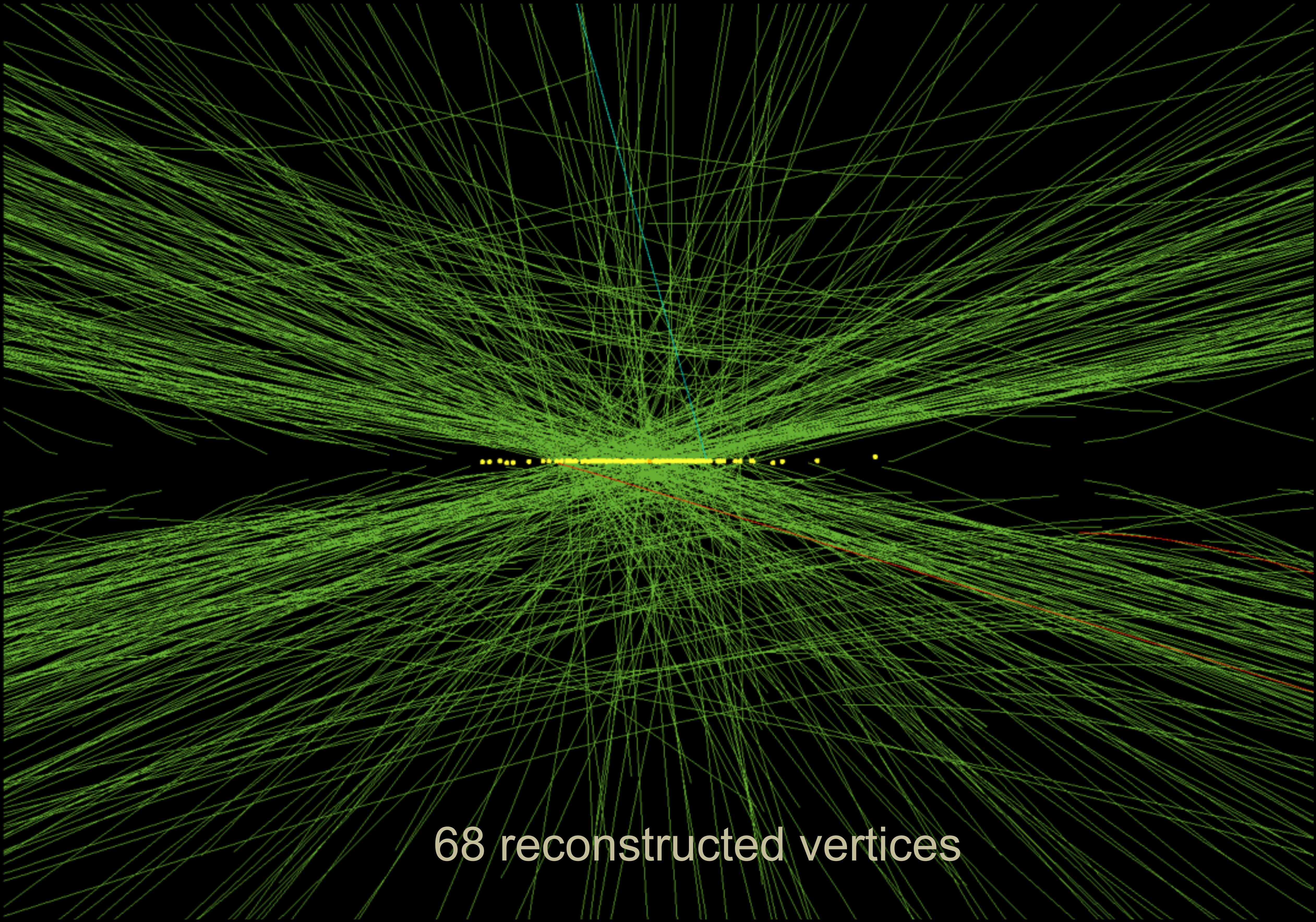
PILE-UP EARLY 2011

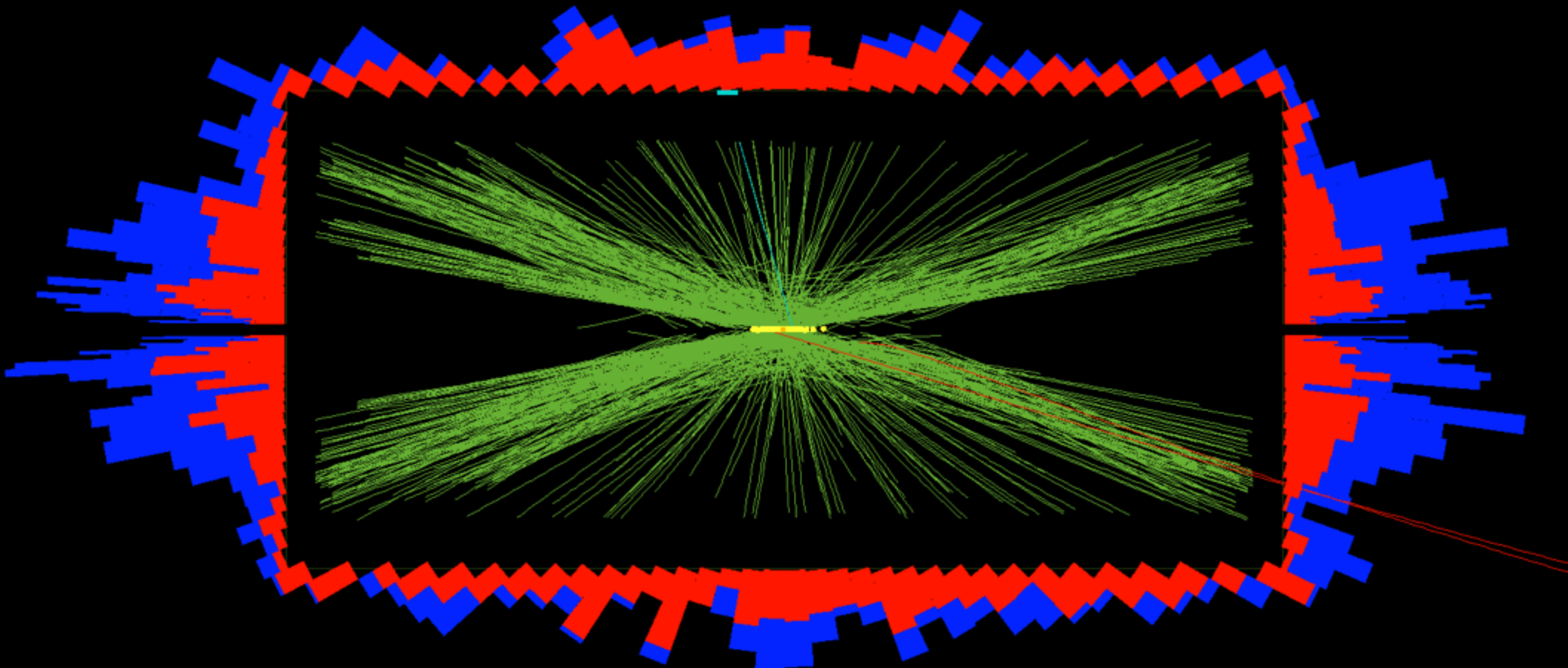


PILE-UP EARLY 2011

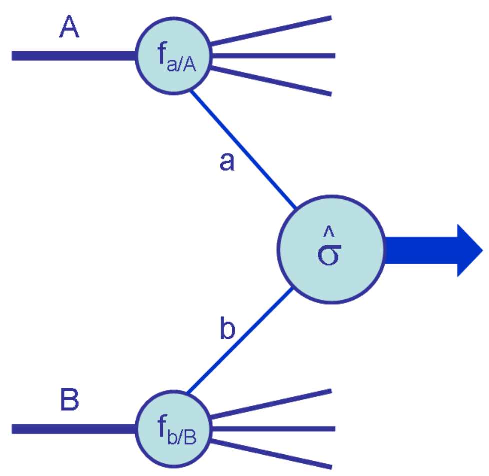


High Pile-Up Event in 2012





HADRONIC CROSS SECTION



$$\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a) f_{b/B}(x_b) \; \hat{\sigma}_{ab\to X}$$

- Successful data/prediction comparison until corrections due to virtual and real gluons computed
  - Large diverging logarithms
- Corrections depend on momentum scale Q^2 of the process
  - e.g. intermediate mass M^2 o p_T^2 of leptons in final state
  - Logarithmic violation of scaling (as already seen in structure functions)

$$\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \; \hat{\sigma}_{ab\to X} \qquad Q^2 = \mu_F^2$$

- Factorization scale: energy scale at which perturbative (short range) and non-perturbative (long range) effects can be separated

Computing Cross Section

- In addition to PDF corrections must take into account also corrections to hard process cross section

$$\sigma_{AB} = \int dx_a dx_b\, f_{a/A}(x_a, \mu_F^2)\, f_{b/B}(x_b, \mu_F^2) \;\times\; [\, \hat{\sigma}_0 \;+\; \alpha_S(\mu_R^2)\, \hat{\sigma}_1 \;+\; \ldots\,]_{ab\to X}$$

- Corrections specific to individual hard processes and cannot be generalized
  - Introduces dependency on QCD renormalization scale μ_R via α_S

- Typically one uses $\mu_R = \mu_F$
  - Value used depends on the process being studied: often m_Z, m_W, p_T^2 of products in final state (jets or leptons) can be appropriate

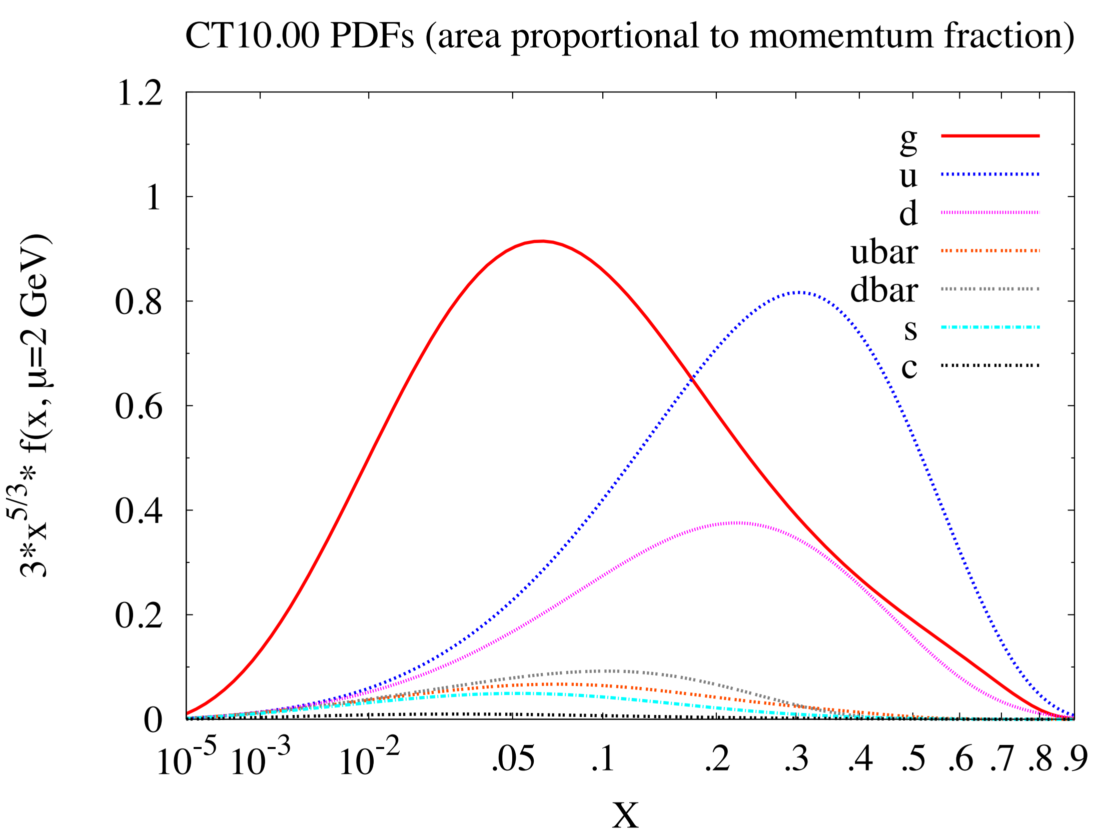
- Cross sections and PDFs must be computed at same perturbation order for large logarithms to cancel each other

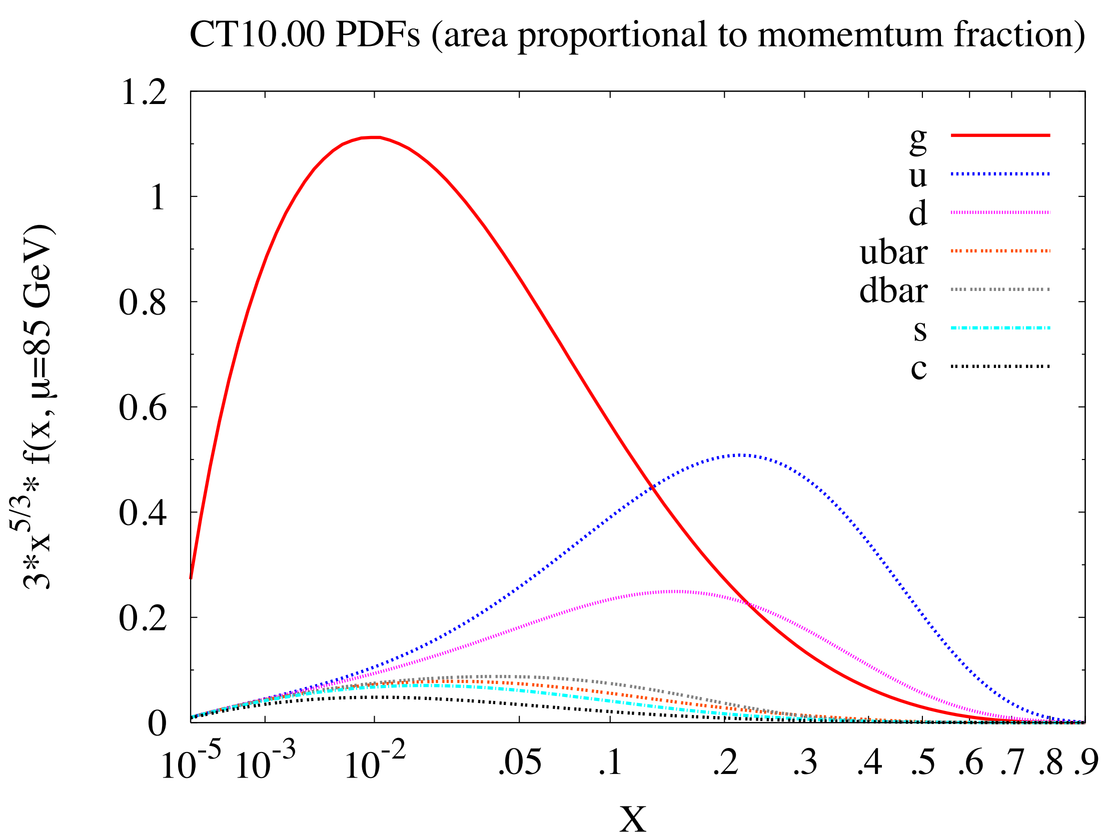
$$\sigma_{AB} = \sum_{a,b=q,g} [\hat{\sigma}_{ab}^{\mathrm{LO}} + \alpha_S(Q^2)\hat{\sigma}_{ab}^{\mathrm{NLO}} + \ldots] \otimes f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2)$$

NLO

EVOLUTION OF PARTON DENSITY FUNCTIONS

- The dependency of PDFs from x is determined from fit to data
  - global fit to fixed target, ep, and collider data
- Dependency of PDFs from momentum scale cannot be computed analytically from first principles
- Single experiments explore different and very specific values of
- In principle one would need to measure each PDF at each scale Q^2!
  - Not practical nor allows to benefit from existing knowledge





gluon momentum fraction grows at higher scales

DOKSHITZER–GRIBOV–LIPATOV–ALTARELLI–PARISI EQUATIONS

- Integro-differential equations to compute PDFs at a desired scale Q^2 given measurements at a different scale

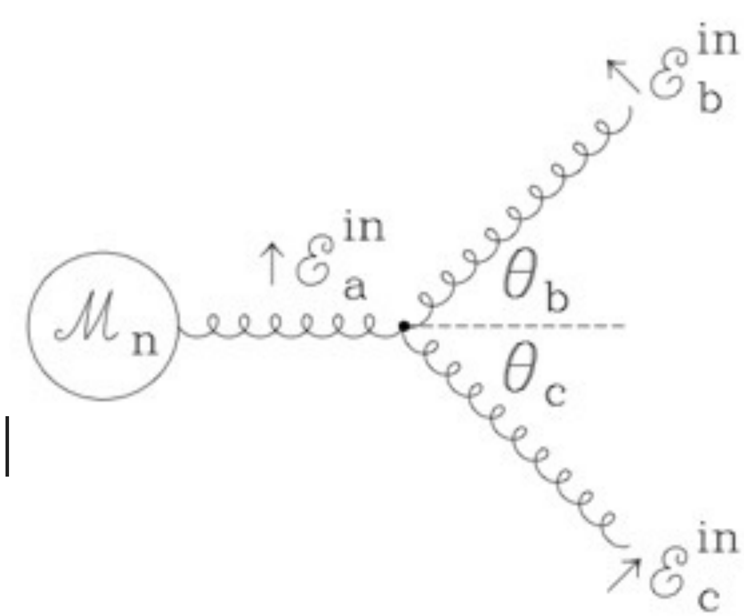
$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{q_i q_j}(y,\alpha_S) q_j(\frac{x}{y},\mu^2) + P_{q_i g}(y,\alpha_S)\, g(\frac{x}{y},\mu^2)\Big\}$$

$$\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{g q_j}(y,\alpha_S) q_j(\frac{x}{y},\mu^2) + P_{gg}(y,\alpha_S) g(\frac{x}{y},\mu^2)\Big\}$$

$$P_{ab}(x,\alpha_S) = P_{ab}^{(0)}(x) + \frac{\alpha_S}{2\pi}P_{ab}^{(1)}(x) + \ldots \qquad a,b = g,q,\bar{q}$$

- Fundamental for having PDFs for LHC processes based on previous experiments

- Splitting functions $P_{ab}(x)$: probability of partons emitting additional quarks or gluons in collinear l
  – depends again on both x and momentum scale

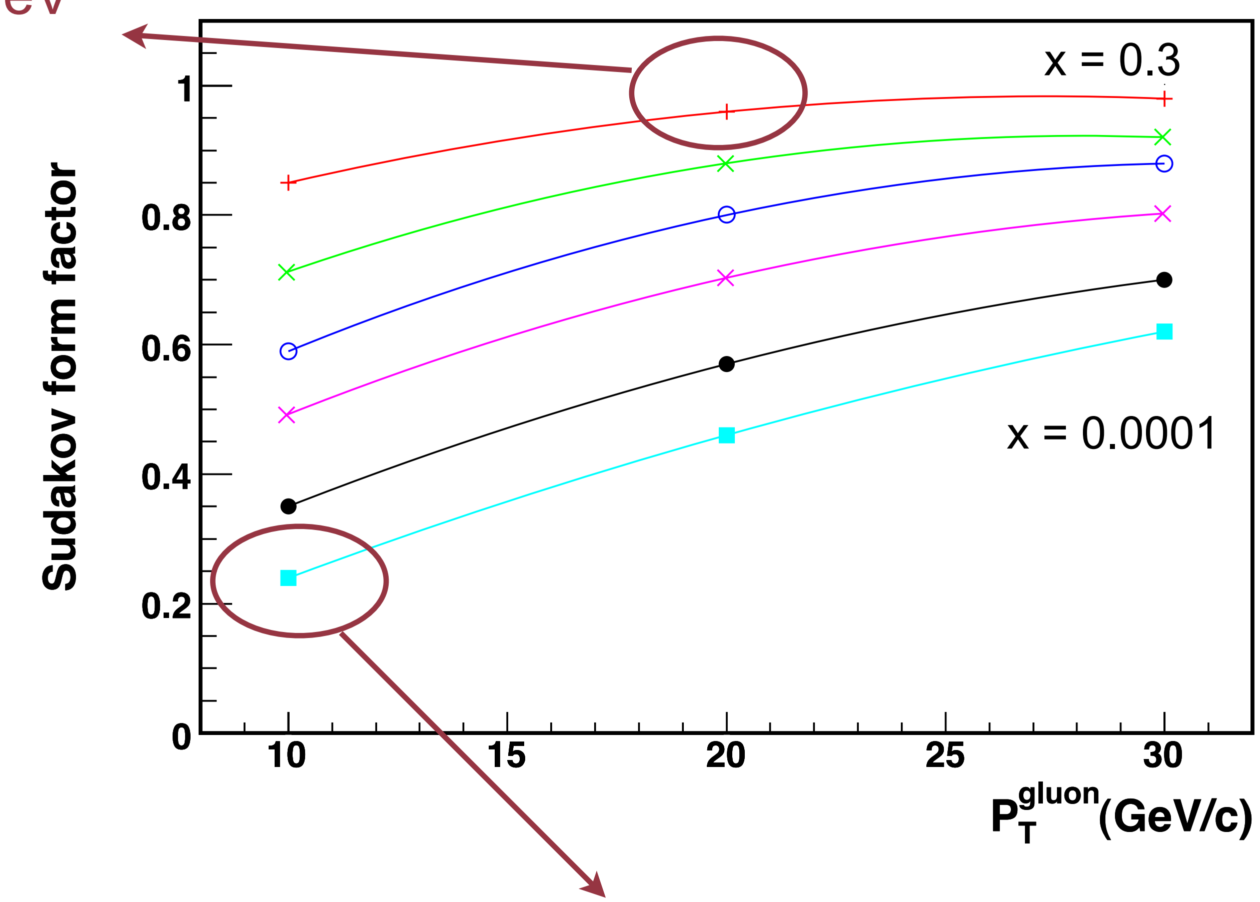


SUDAKOV FORM FACTORS

- Probability of parton evolution for softer scale without emission of partons
- Gluons are dominant at LHC hence gluon splitting is most important
- Probability of a initial-state gluon at momentum scale of 100 GeV NOT emitting a gluon of given p_T
- Depends on
  - parton type
  - hard process scale
  - intial parton x

- Non-emission probability lower for
  - lower p_T for emitted gluon
    - more gluons can be emitted for given energy
  - lower momentum initial parton has larger emission phase space

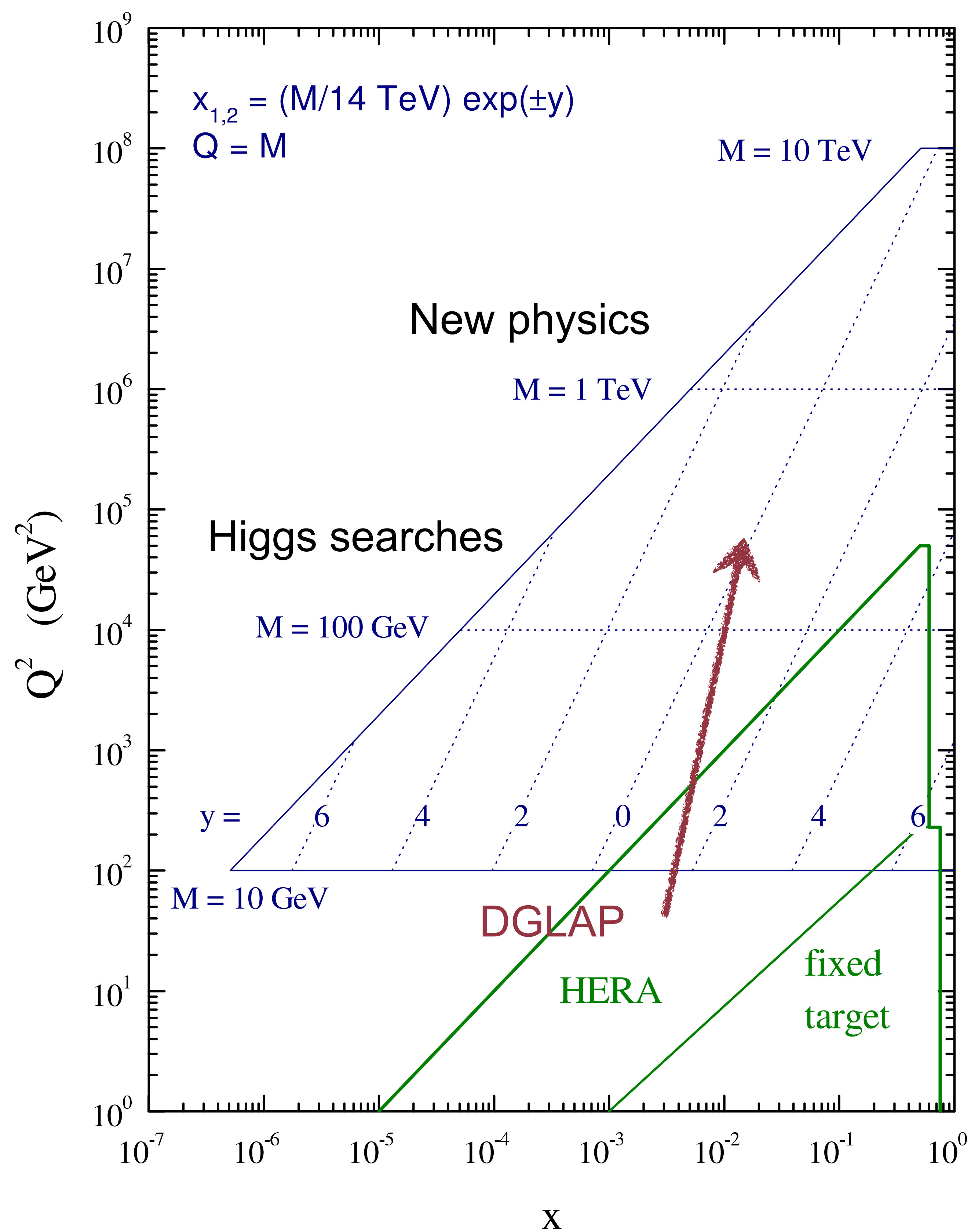
10% probability of emitting a gluon with pT of 20 GeV



80% probability of emitting a gluon with p_T of 10 GeV

LHC Parton Kinematics

- For $y = 0$ need $x_1 \sim x_2$:
  - partons have similar x
  - small longitudinal boost
  - parton center of of mass almost at rest
- New heavy particles need relatively large values of x
- Producing particles at large rapidity (y ~ 2 or more) implies very different x for incoming partons
- Heavy vector bosons Z' and W' excluded for < 2 TeV
- Higgs searches: 100-200 GeV



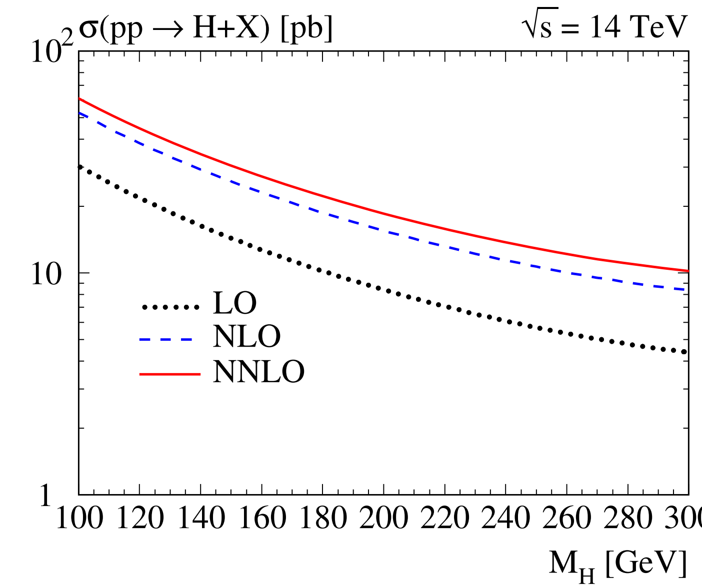
K-FACTOR

- Express strength of Next-to-Leading-Order corrections compared to Leading Order (LO)

$$\mathcal{K} = \frac{\sigma_{NLO}(PDF\,NLO)}{\sigma_{LO}(PDF\,LO)} \qquad \mathcal{K}' = \frac{\sigma_{NLO}(PDF\,LO)}{\sigma_{LO}(PDF\,LO)}$$

  – typically use PDF at same order as the cross section

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W+1$ jet	m_W	$\langle p_T^{\text{jet}}\rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W+2$ jets	m_W	$\langle p_T^{\text{jet}}\rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\text{jet}}\rangle$	1.07	0.97	1.07	1.23	1.34	1.09



- Caveat: commonly used as just one number but can strongly depend on phase space
  – kinematic cuts can change significantly the K factor
  – can be affected by large uncertainties for specific hard processes and/or selection requirements of individual analyzes
- Usually used in experiments to re-weight simulated events
  – Common source of systematic uncertainty in cross section measurement

Parton Luminosity

Comparing Data at Different Center of Mass Energy

CROSS SECTION FOR FIXED PARTON CMS ENERGY

$$\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \; \hat{\sigma}_{ab\to X}$$

- Calculation sums over all values of x for each parton but they are not independent if we look at processes with given $\hat{s}$
  - s is fixed for given operating point: 8 TeV @ LHC, 1.96 TeV @ Tevatron

$$\hat{s} = x_1 x_2 s \qquad\qquad \tau = x_1 x_2 = \frac{\hat{s}}{s}$$

- if we fix value of $\hat{s}$ then only one of the two x_i can vary $\delta(x_1 x_2 s - \hat{s})$

$$\sigma_{AB} = \int dx_a dx_b \; f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \; \hat{\sigma}_{ab\to X}$$

$$dx \frac{d\tau}{x} f_{a/A}(x, Q^2) f_{b/B}(\tau/x, Q^2) \qquad\qquad \tau = \frac{\hat{s}}{s} \to 1$$

Parton Luminosity

$$\frac{\tau}{\hat{s}}\frac{d\mathcal{L}_{ij}}{d\tau} \equiv \frac{\tau/\hat{s}}{1+\delta_{ij}} \int_\tau^1 dx[f_i^{(a)}(x)f_j^{(b)}(\tau/x) + f_j^{(a)}(x)f_i^{(b)}(\tau/x)]/x$$

$$\sigma(s) = \sum_{\{ij\}} \int_{\tau_0}^1 \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}}\frac{d\mathcal{L}_{ij}}{d\tau} \cdot \boxed{[\hat{s}\hat{\sigma}_{ij\to\alpha}(\hat{s})]}$$

Can be roughly estimated
by coupling constants

- quantity with dimensions of a cross section commonly referred to a "parton luminosity"
  - very bad and confusing choice but by now largely used in literature
  - In practice a weight factor in front of parton level hard process cross section
  - Determines which hard process is dominating in total cross section for given

$$\tau = x_1 x_2 = \frac{\hat{s}}{s}$$

Why Do We Care about Parton Luminosity?

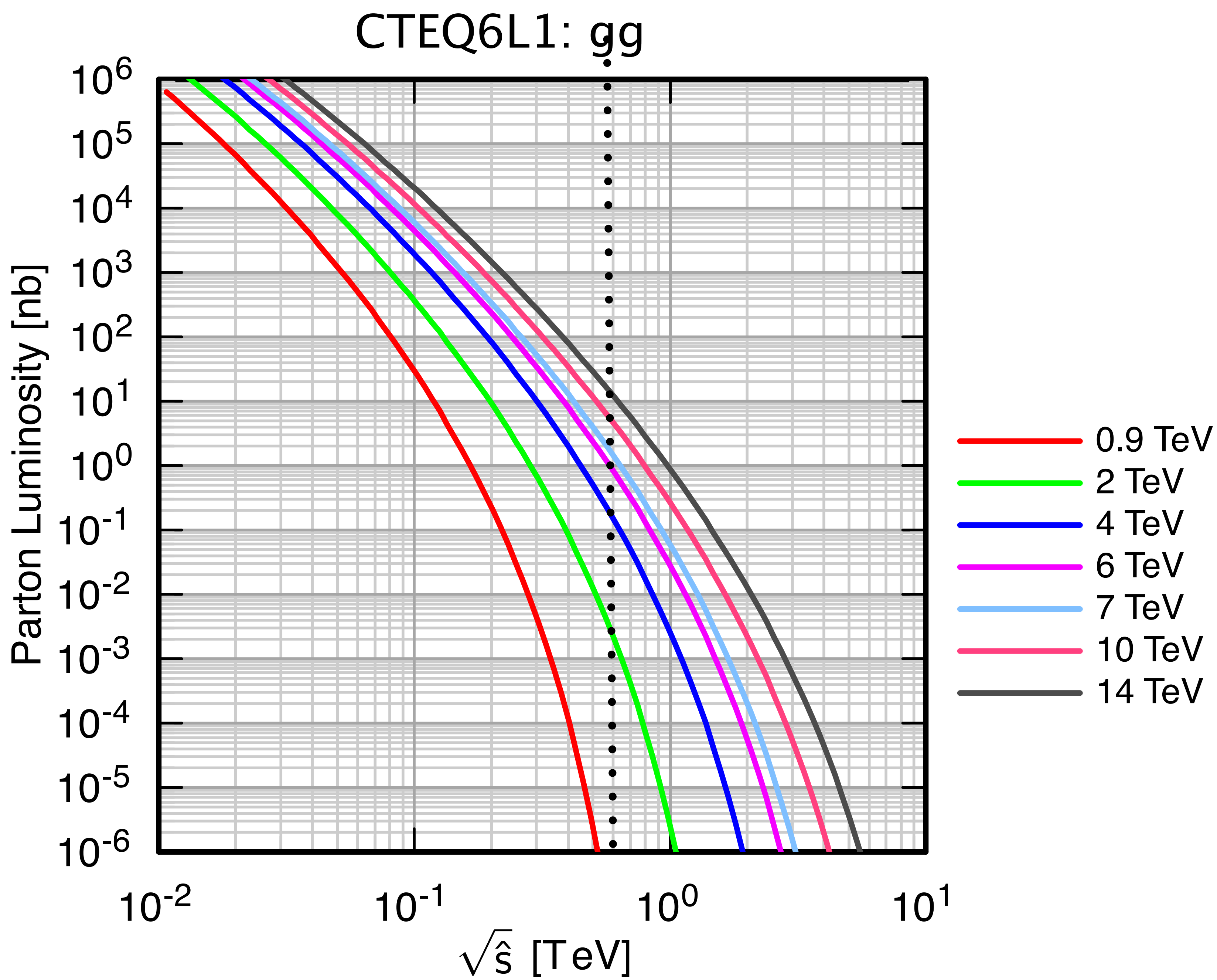
- Hard process cross section calculation independent from particle accelerator or center of mass
  - except for kinematic phase space factors and requirements

- Final states can be in common for Tevatron and LHC although different types of hadron collisions and different parton level diagrams

- Parton luminosity allows to compare cross sections at different energies and between proton-proton vs proton-antiproton

- For a signal process if sources of background are known we can use parton luminosity to estimate S/B at different center-of-mass energies
  - Currently being used to estimate LHC performance and comparison with Tevatron if running at 13 TeV in 2015

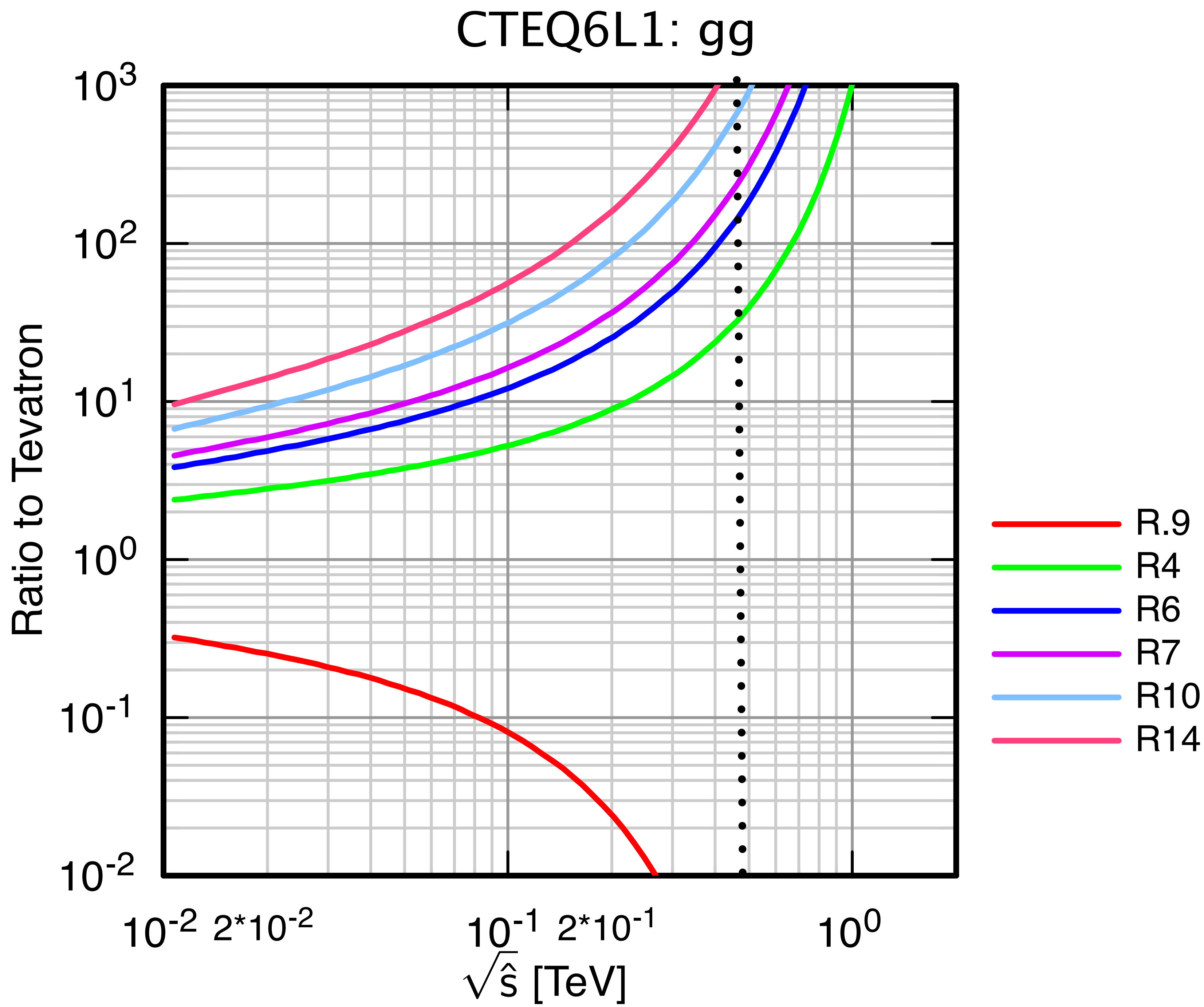
GLUON-GLUON FUSION



- Loss of an order of magnitude running at 7 TeV instead of 14 TeV!
- Significant for new physics searches
- reduction in cross section implies longer data taking period to accumulate same number of events needed for discovery or exclusion

$$N = \mathcal{L}_{inst} \times \sigma \times \Delta t = \mathcal{L}_{int} \times \sigma$$

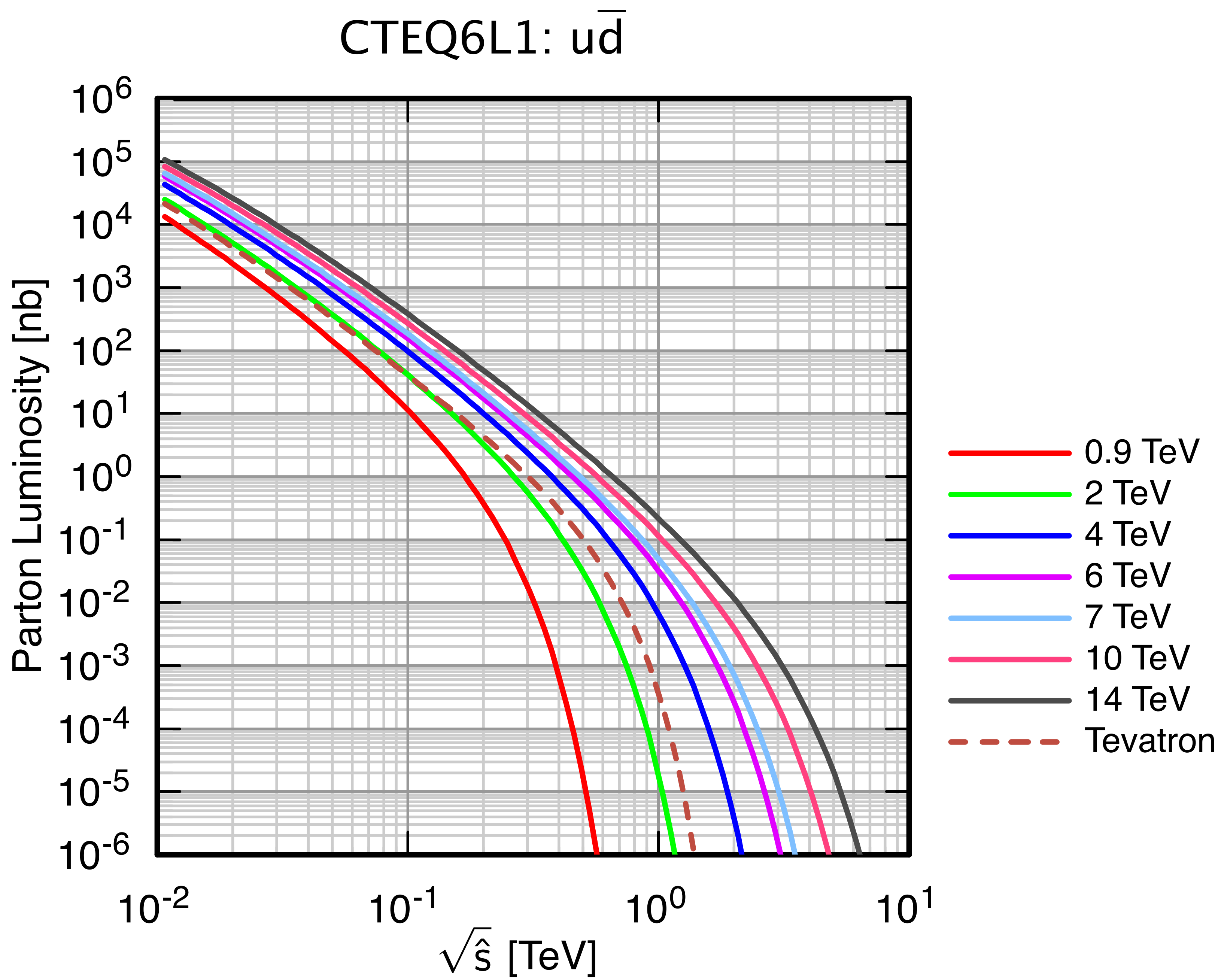
GLUON-GLUON: LHC VS. TEVATRON



- x100 gain in gluon-gluon fusion processes at 7 TeV compared to Tevatron for $\sqrt{\hat{s}} \sim 0.5\,TeV$
- Competitive results from LHC with much less data
- gg processes play critical role in Higgs discovery at LHC!

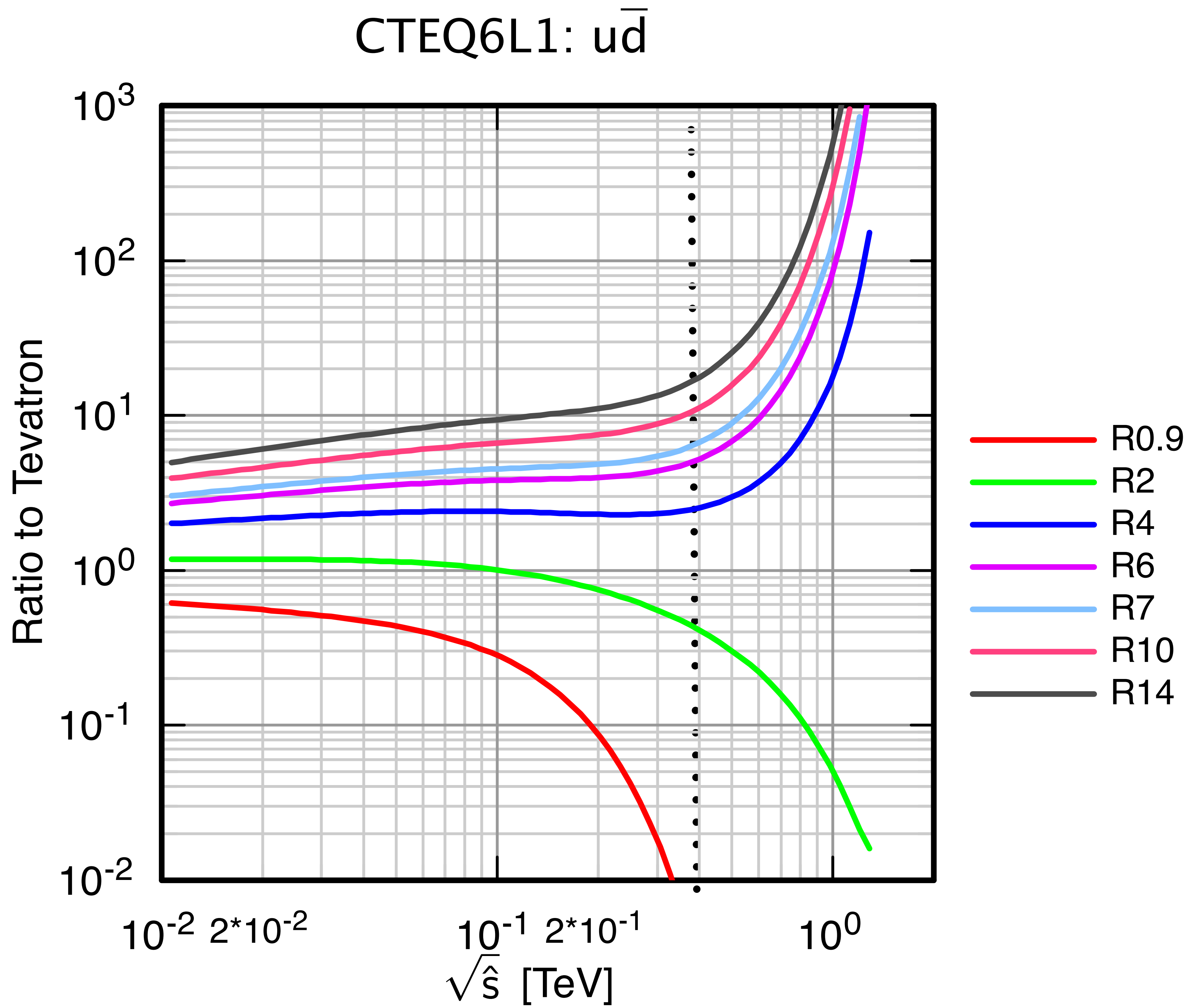
$$\mathcal{L}_{int}^{LHC} \times \sigma_{LHC} = \mathcal{L}_{int}^{tevat.} \times \sigma_{tevat.}$$

QUARK-ANTI-QUARK PROCESS



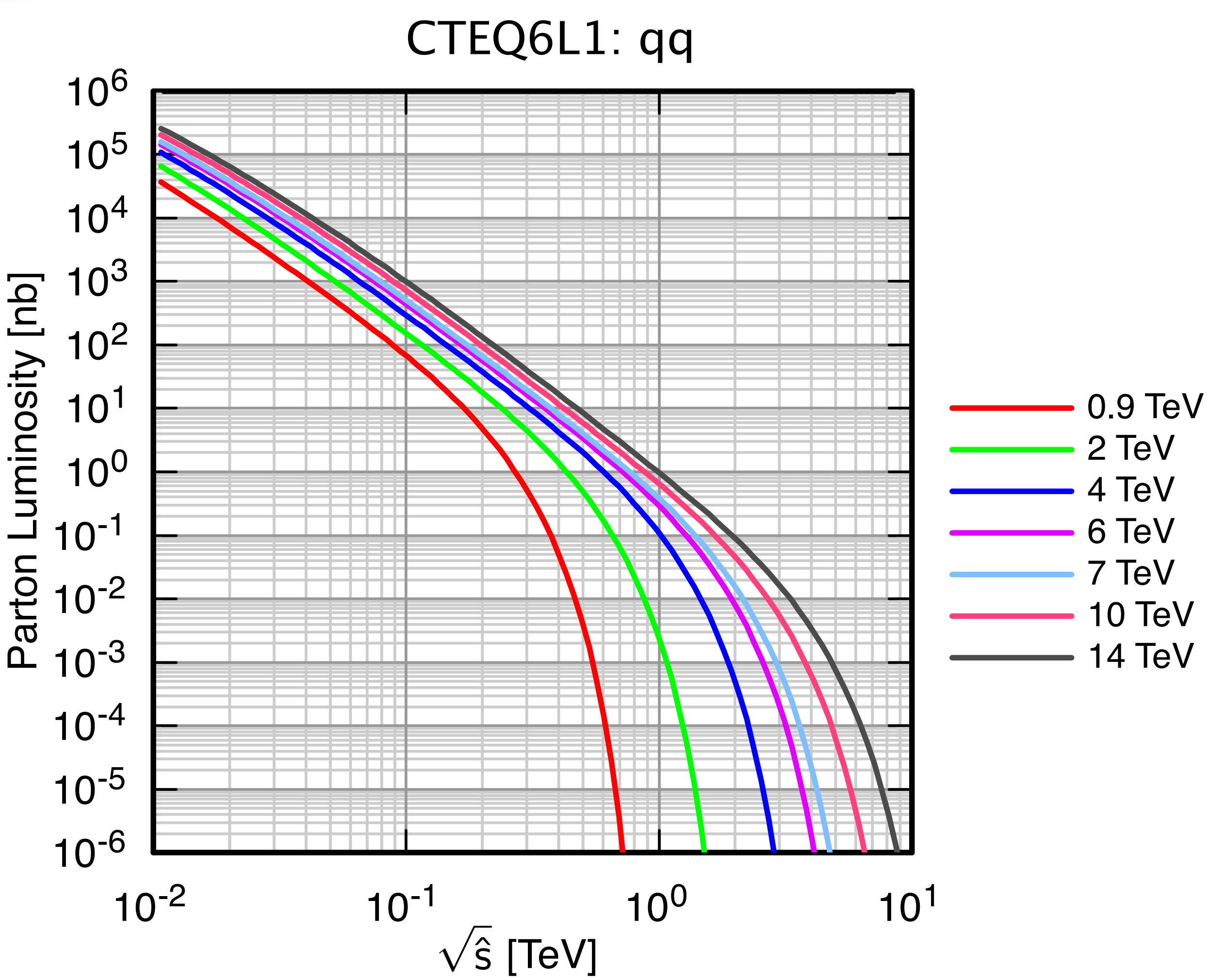
- Major difference between Tevatron and LHC
  - only sea anti-quarks at LHC
- Smaller gain for higher center of mass energy at LHC

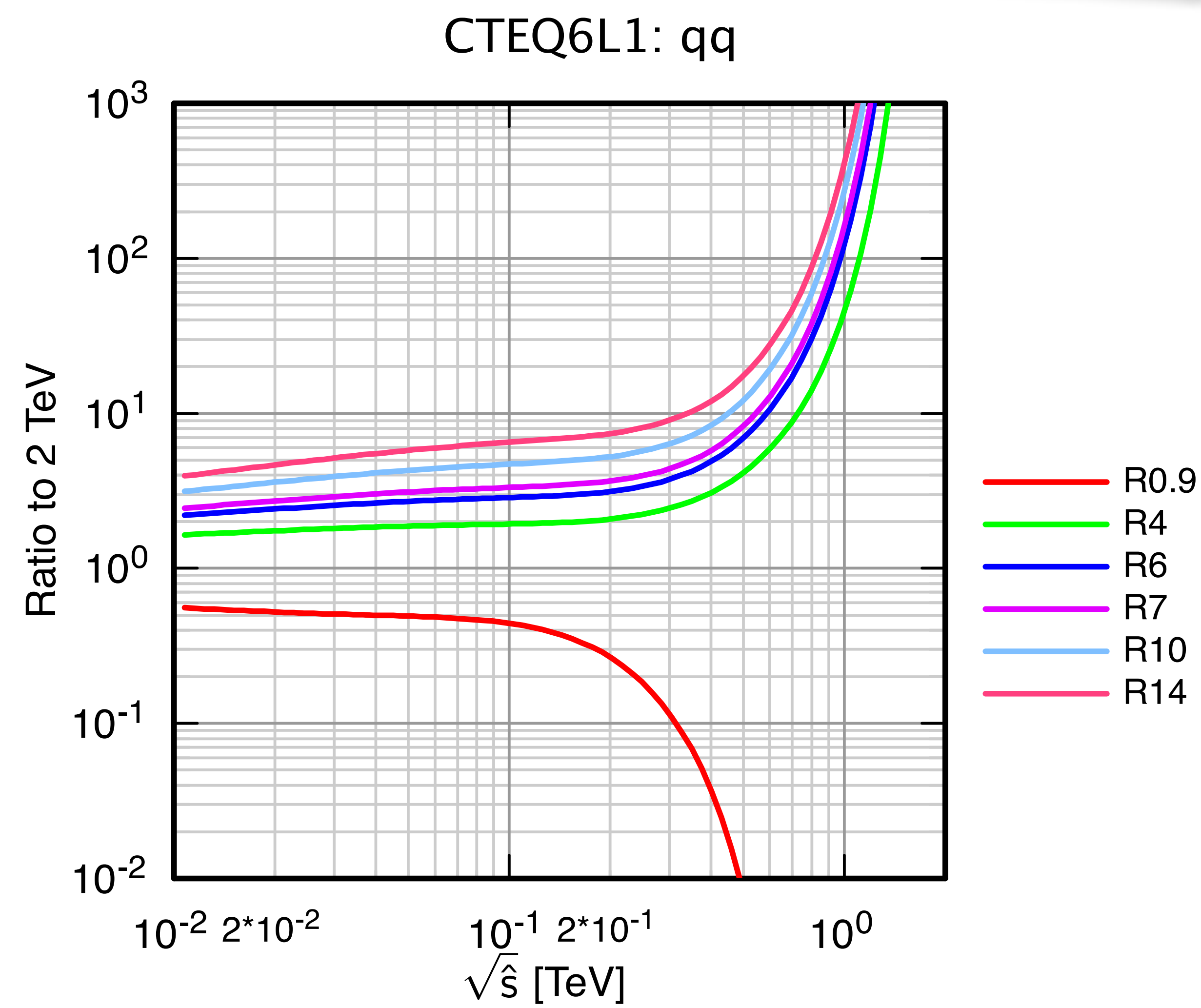
QUARK-ANTIQUARK: LHC VS. TEVATRON



- Moderate gain of LHC on Tevatron but much less compared to gluon-gluon
  - Competition with Tevatron more challenging and open in 2011 for final states dominated by this hard process

QUARK-QUARK PROCESS





- Moderate but not huge gain at LHC even at 14 TeV
- gluon-gluon fusion is critical for higgs and new physics discovery at LHC

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