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Particle Physics Phenomenology
9. Total Cross Sections and Generator Physics

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Units and naive cross sections

Natural size : length 1 fm $= 10^{-15}$ m
$\Rightarrow$ area 1 fm$^2 = 10^{-30}$ m^2

Historically: 1 barn = 1 b $= 10^{-24}$ cm$^2 = 10^{-28}$ m^2
$\Rightarrow$ 1 mb $= 10^{-3}$ b $= 10^{-31}$ m$^2 = 0.1$ fm^2

Outdated, but recall that $[\mathcal{L}] = \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

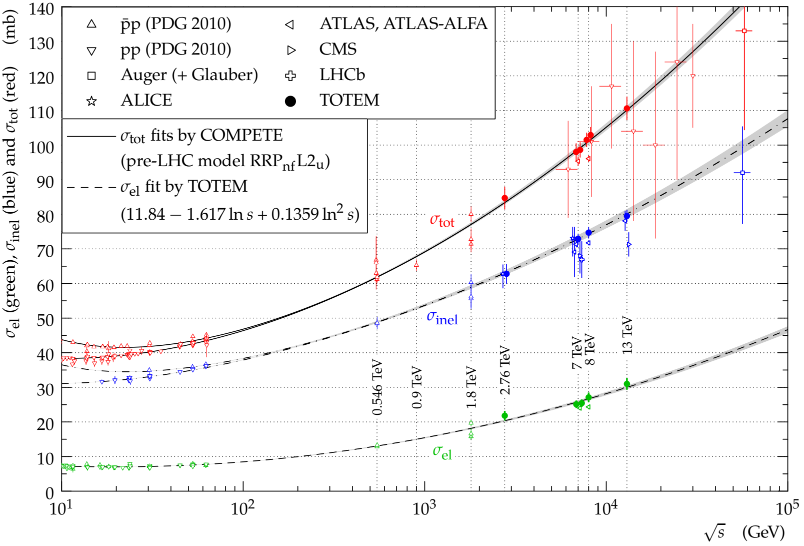
Proton radius $r_{\mathrm{p}} \approx 0.7$ fm
$\Rightarrow$ area $A_{\mathrm{p}} \approx \pi r_{\mathrm{p}}^2 \approx 1.5$ fm$^2 \to 1$ fm^2 since 2 of 3 dimensions.

Total hadronic cross section $\approx$ when two protons overlap ?

$\Rightarrow \sigma_{\mathrm{pp}} \approx \pi(2r_{\mathrm{p}})^2 \approx 4$ fm$^2 =$ 40 mb.

$\sigma_{\mathrm{pp}}^{\mathrm{QED}} = \infty$ since protons are charged,
but for $\mathrm{pp} \to \mathrm{pp}$ elastic scattering in $\theta \to 0$ limit $\Rightarrow$ unmeasurable
Conventionally: $\sigma_{\mathrm{pp}}^{\mathrm{tot}} = \sigma_{\mathrm{pp}}^{\mathrm{QCD}}$

Total cross section



Impact-parameter MPI unitarization

Here naive model — more sophisticated later

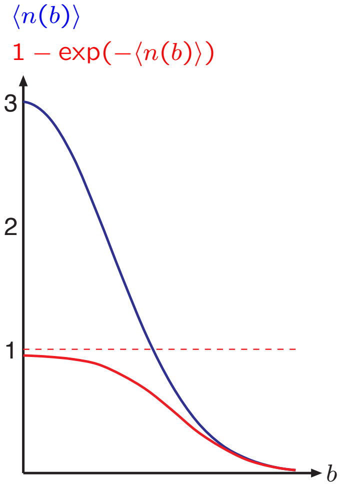
Assume Poissonian distribution of $\langle n(b) \rangle$, i.e. average number of MPI at impact parameter b:

$$\begin{aligned} P_i(b) &= \frac{\langle n(b) \rangle}{i!} \exp(-\langle n(b) \rangle) \\ P_0(b) &= \exp(-\langle n(b) \rangle) \\ P_{\geq 1}(b) &= 1 - \exp(-\langle n(b) \rangle) \end{aligned}$$

$$\sigma_{\mathrm{MPI}} = \int \mathrm{d}^2 b \, (1 - \exp(-\langle n(b) \rangle))$$

Increasing energy $\Rightarrow$ more MPI:

- Bigger: non-negligible to larger b
- Blacker: $P_{\geq 1}(b) \to 1$ for small b
- Edgier?: rim $P_{\geq 1}(b) \approx 0.5$ thinner

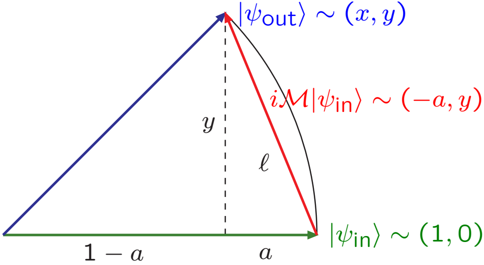


$$|\psi_{\mathrm{out}}\rangle = S\,|\psi_{\mathrm{in}}\rangle = (1 + i\mathcal{M})\,|\psi_{\mathrm{in}}\rangle$$

Unitarity: conservation of probability:

$$S^\dagger S = 1 \Rightarrow (1 - i\mathcal{M}^\dagger)(1 + i\mathcal{M}) = 1$$

$$\Rightarrow i(\mathcal{M} - \mathcal{M}^\dagger) + \mathcal{M}^\dagger\mathcal{M} = 0 \Rightarrow 2\,\mathrm{Im}\mathcal{M} = \mathcal{M}^\dagger\mathcal{M}$$



$$\begin{aligned} x &= 1 - a \\ y &= \sqrt{1 - x^2} \\ &= \sqrt{1 - (1 - a)^2} \\ &= \sqrt{2a - a^2} \\ \ell^2 &= (-a)^2 + y^2 \\ &= a^2 + 2a - a^2 = 2a \end{aligned}$$

The optical theorem – 2

Introduce 2-body in-state $|ab\rangle$,
and complete set of possible final states $|n\rangle$: $\sum_n |n\rangle\langle n| = 1$

$$
\begin{aligned}
2\,\mathrm{Im}\langle ab|\mathcal{M}|ab\rangle &= \langle ab|\mathcal{M}^\dagger\mathcal{M}|ab\rangle \\
&= \sum_n \langle ab|\mathcal{M}^\dagger|n\rangle\langle n|\mathcal{M}|ab\rangle \\
&= \sum_n |\langle n|\mathcal{M}|ab\rangle|^2
\end{aligned}
$$

$\mathrm{Im}\,\langle ab|\mathcal{M}|ab\rangle \sim$ amplitude for forward ($t = 0$) elastic scattering,

$\sum_n |\langle n|\mathcal{M}|ab\rangle|^2 \sim$ total cross section to all possible final states,

$$
\Rightarrow \frac{\mathrm{d}\sigma_{\mathrm{el}}(s, t = 0)}{\mathrm{d}t} \propto \sigma_{\mathrm{tot}}^2(s)
$$

If you understand the elastic cross section you get the total for free.

The optical theorem and unitarization

Eikonal function $\chi(b, s)$, for now real, gives scattering amplitude

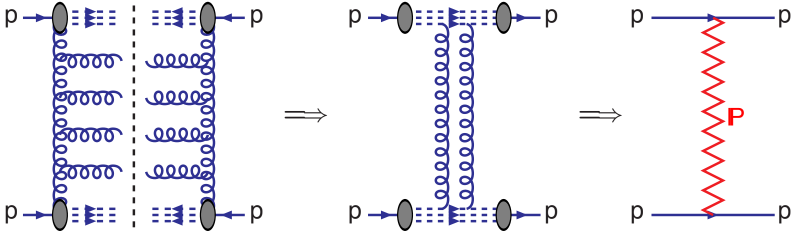
$$\begin{aligned}
\sigma_{\mathrm{tot}}(s) &\sim \mathrm{Im}\, f(s,0) = 2 \int \mathrm{d}^2 b \left(1 - e^{-\chi(b,s)}\right) \\
\sigma_{\mathrm{el}}(s) &\sim |f(s,t)|^2 = \int \mathrm{d}^2 b \left(1 - e^{-\chi(b,s)}\right)^2 \\
\sigma_{\mathrm{inel}}(s) &= \sigma_{\mathrm{tot}}(s) - \sigma_{\mathrm{el}}(s) = \int \mathrm{d}^2 b \left(1 - e^{-2\chi(b,s)}\right)
\end{aligned}$$

Associate $\sigma_{\mathrm{MPI}}(s) = \sigma_{\mathrm{inel}}(s) \quad \Rightarrow \quad 2\chi(b,s) = \langle n(b) \rangle$ or

$$\begin{aligned}
\chi(b,s) &= \frac{1}{2} \sigma_{\mathrm{MPI}}(s)\, A(b) \\
A(\mathbf{b}) &= \int \mathrm{d}^2 b'\, G(\mathbf{b}')\, G(\mathbf{b} - \mathbf{b}') \\
\int \mathrm{d}^2 b\, A(\mathbf{b}) &= \int \mathrm{d}^2 (\mathbf{b} - \mathbf{b}')\, G(\mathbf{b} - \mathbf{b}') \int \mathrm{d}^2 \mathbf{b}'\, G(\mathbf{b}') = 1
\end{aligned}$$

The Pomeron

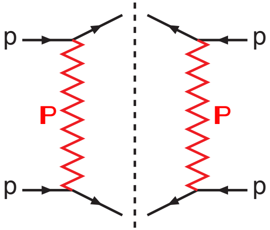
Amplitude for (forward) elastic scattering from total cross section:



introducing the Pomeron $\mathbb{P}$ as shorthand for the effective 2-gluon exchange.

Since $\mathrm{p} \to \mathrm{p}\,\mathbb{P}$ the Pomeron must have the quantum numbers of the vacuum: 0^+ colour singlet.

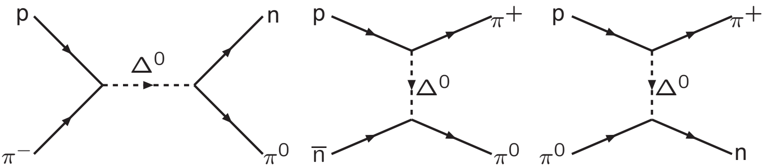
Recall: elastic cross section requires squaring one more time:



Field theory

Historically, the Pomeron precedes QCD and (established) quarks.
Instead based on general properties of field theory;

- Unitarity: optical theorem.
- Crossing: if $\mathcal{M}(s,t,u)$ describes $1+2 \to 3+4$
  then $\mathcal{M}(t,s,u)$ describes $1+\overline{3} \to \overline{2}+4$
  and $\mathcal{M}(u,t,s)$ describes $1+\overline{4} \to 3+\overline{2}$.



- Analyticity: $\mathcal{M}$ analytic function of s, t, u
  $\Rightarrow$ poles, branch cuts, dispersion relations, ...
- Regge theory.

Regge theory – 1

Start with elastic-scattering partial-wave series in s channel:

$$\mathcal{M}(s,t) = \sum_{J=0}^{\infty} (2J+1)\,\mathcal{M}_J(s)\,P_J(\cos\theta)$$

where J is s-channel angular momentum,
P_J Legendre polynomials, and

$$\cos\theta = 1 + \frac{2t}{s-4m^2} \quad \text{if} \quad m_1^2 = m_2^2 = m_3^2 = m_4^2 = m^2 \ .$$

Cross to t-channel

$$\mathcal{M}(s,t) = \sum_{J=0}^{\infty} (2J+1)\,\mathcal{M}_J(t)\,P_J(\cos\theta_t) \quad \text{with} \quad \cos\theta_t = 1 + \frac{2s}{t-4m^2} \ .$$

For $s \to \infty$, t fixed: $\cos\theta_t \to -\infty$:

$$P_J(\cos\theta_t) \sim (\cos\theta_t)^J \sim s^J$$

Regge theory – 2

Gives divergent series

$$\mathcal{M}(s,t) = \sum_{J=0}^{\infty} (2J+1)\, s^J\, f_J(t)$$

so resum with analytic continuation,
using $J \to \alpha$ as complex variable.

Simple example: $1 + x + x^2 + x^3 + \ldots$ badly divergent for $x > 1$,
but resums to $1/(1-x)$, which is finite except in pole $x = 1$.

Result: if there exists a "trajectory" of particles $\alpha(t)$,
i.e. straight line of poles corresponding to integer or half-integer α,
then $\mathcal{M}(s,t) \sim f(t)\, s^{\alpha(t)}$
and $\sigma_{\mathrm{tot}} \sim \mathcal{M}(s,0)/s \sim s^{\alpha(0)-1}$.

Regge trajectories

Linear trajectories $\alpha(t) = \alpha(0) + \alpha' t$
both in meson and baryon sector:

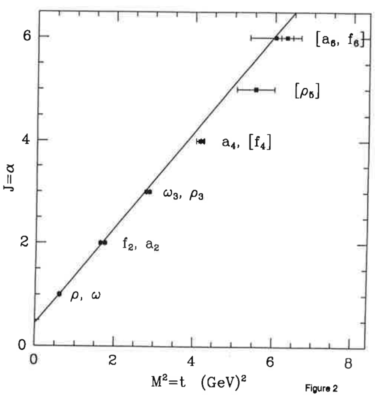


Figure 2

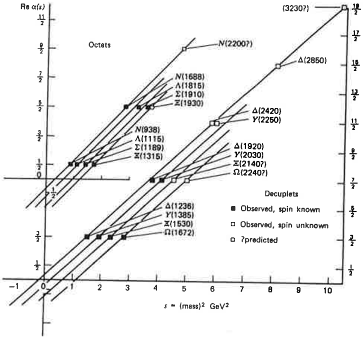
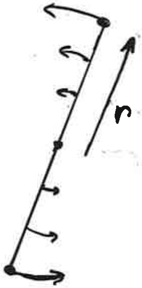


Fig. 17-8 A Chew-Frautschi plot for baryons. The lines, which are assumed to be Regge trajectories, connect baryon families with the same *I*, *B*, and *S* (17CHI). Reproduced with permission from "Evidence for Regge Poles and Hadron Collision Phenomena at High Energies," *Annual Review of Nuclear Science*, 22, 263 (1972). Copyright © by Annual Reviews, Inc., 1972. All rights reserved.

Most important is ρ trajectory with intercept $\alpha(0) \approx 0.5$.

Why linear trajectory?

View a meson at rest as a stiffly rotating string
with endpoint quarks moving at the speed of light
$0 \leq r \leq d$, $v(r) = r/d$, $\gamma(r) = 1/\sqrt{1 - r^2/d^2}$

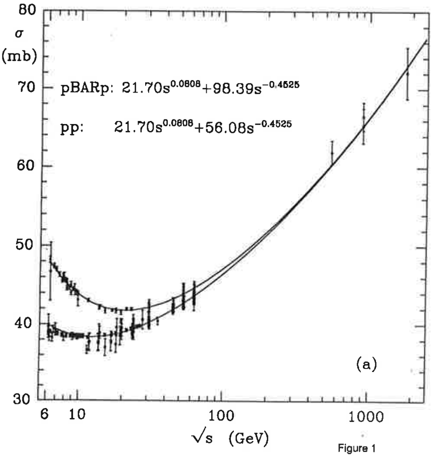


$$
\begin{aligned}
m &= 2 \int_0^d \mathrm{d}r \, \kappa\gamma(r) = 2\kappa d \int_0^1 \frac{\mathrm{d}y}{\sqrt{1-y^2}} = \pi\kappa d \\
L &= 2 \int_0^d \mathrm{d}r \, r \, \kappa v(r)\gamma(r) = 2\kappa d^2 \int_0^1 \frac{y^2 \, \mathrm{d}y}{\sqrt{1-y^2}} \\
&= \frac{\pi}{2}\kappa d^2 = \frac{m^2}{2\pi\kappa} \\
\alpha' &= \frac{\mathrm{d}\alpha}{\mathrm{d}t} = \frac{\mathrm{d}L}{\mathrm{d}m^2} = \frac{1}{2\pi\kappa}
\end{aligned}
$$

Data $\alpha' \approx 0.9$ GeV^{-2} gives $\kappa \approx 0.9$ GeV/fm.

Linear Regge trajectories and linear confinement are closely related!

The Reggeon(s)



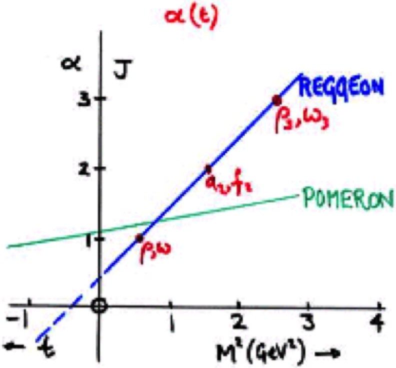
The ρ trajectory has
$\alpha(0) \approx 0.5$
$\Rightarrow \sigma_{\mathrm{tot}} \approx s^{-0.5}$:
required for low energies
but not enough.

$$\sigma_{\mathrm{tot}}^{\mathrm{p\overline{p}}} \approx 21.7\, s^{0.08} + 98.4\, s^{-0.45}$$
$$\sigma_{\mathrm{tot}}^{\mathrm{pp}} \approx 21.7\, s^{0.08} + 56.1\, s^{-0.45}$$

Pomeron term "universal",
while Reggeon contributions
are process-dependent:
pp only ρ^0 exchange $\mathrm{pp} \to \mathrm{pp}$
while $\mathrm{p\overline{p}}$ has $\mathrm{p\overline{p}} \to \mathrm{p\overline{p}}$
and $\mathrm{p\overline{p}} \to \mathrm{n\overline{n}}$.

The Pomeron trajectory

$\alpha(t) = \alpha(0) + \alpha' \, t = 1 + \epsilon + \alpha' \, t.$
Critical Pomeron (original): $\epsilon = 0 \Rightarrow \sigma_{\mathrm{tot}}$ constant.
Supercritical Pomeron: $\epsilon > 0 \Rightarrow \sigma_{\mathrm{tot}}$ rises.



Need a trajectory with intercept $\alpha(0) \approx 1.08$.

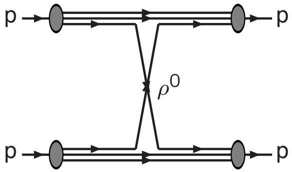
Consistent with spin-2 glueball around $m = 2$ GeV, but mixing $\mathrm{gg} \leftrightarrow \mathrm{q\overline{q}g} \leftrightarrow \mathrm{q\overline{q}}$ leaves no clear glueball.

Excess number of neutral states consistent with it, however.

Purist's view: the Pomeron is not a physical state, only a field theoretical construction.

Trajectories and PDFs

The Regge limit, t fixed and $s \to \infty$ corresponds to $x \to 0$.

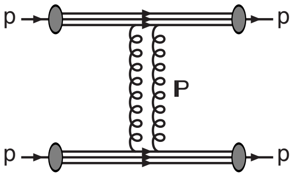


related to exchange of valence quarks

$$\sigma_{\mathrm{tot,Reggeon}} \propto 1/\sqrt{s}$$
$$\Rightarrow \quad q_{\mathrm{val}} \propto 1/\sqrt{x}$$

or more properly

$$q(x) = N_q \, \frac{(1-x)^{n_q}}{\sqrt{x}}$$



related to exchange of gluons (and sea quarks)

$$\sigma_{\mathrm{tot,Pomeron}} \propto 1/s^{1.08}$$
$$\Rightarrow \quad g \propto 1/x^{1.08}$$

or more properly

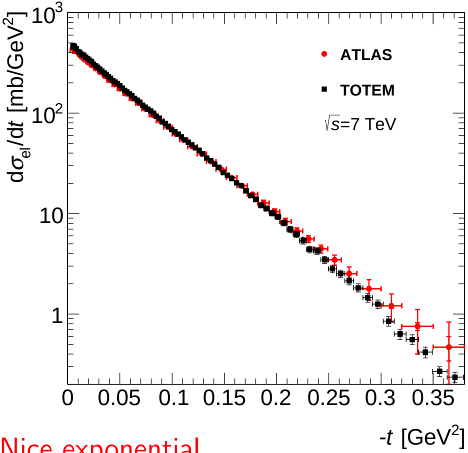
$$g(x) = N_g \, \frac{(1-x)^{n_g}}{x^{1.08}}$$

Elastic scattering

Recall $\mathcal{M}(s,t) \approx C\, f(t)\, s^{\alpha(t)}$, with $\alpha(t) \approx \alpha(0) + \alpha' t$.
Here $f(t)$ form factor, amplitude that hadrons do not break up.
Simple ansatz $f(t) \approx \exp(b_A t)\, \exp(b_B t)$ for $A + B \to A + B$.
Dimensional consistency $s \to s/s_0 = \overline{s}$;
e.g. with $s_0 = 1/\alpha' = 4$ GeV^2.

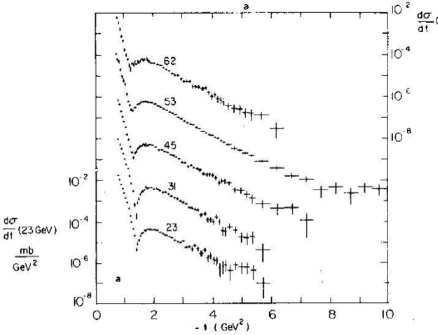
$$\begin{aligned}
\mathcal{M}(s,t) &\approx i\, C\, \exp(b_A t)\, \exp(b_B t)\, \overline{s}^{\alpha(0)+\alpha' t} \\
&= i\, C\, \overline{s}^{\alpha(0)}\, \exp\left((b_A + b_B + \alpha' \ln \overline{s}\,)t\right) \\
B_{\mathrm{el}} &= 2\,(b_A + b_B + \alpha' \ln \overline{s}) \\
\sigma_{\mathrm{tot}} &= \frac{\mathrm{Im}\mathcal{M}(s,0)}{s} = C\, \overline{s}^{\alpha(0)} \\
\mathrm{d}\sigma_{\mathrm{el}} &= \frac{|\mathcal{M}(s,t)|^2}{2s}\, \frac{\mathrm{d}t}{8\pi s} = \frac{|\mathcal{M}(s,0)|^2\, \exp(B_{\mathrm{el}}\, t)}{s^2}\, \frac{\mathrm{d}t}{16\pi} \\
&= \sigma_{\mathrm{tot}}^2\, \exp(B_{\mathrm{el}}\, t)\, \frac{\mathrm{d}t}{16\pi}
\end{aligned}$$

The differential elastic cross section



Nice exponential
at intermediate $|t|$ values.

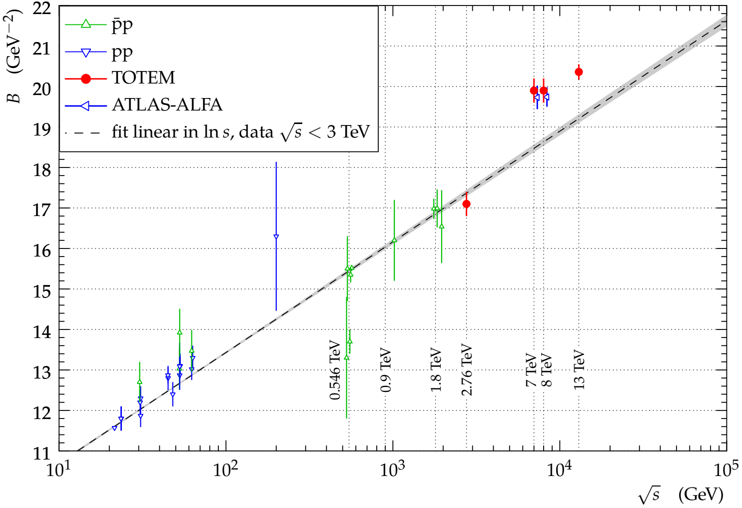
ISR:



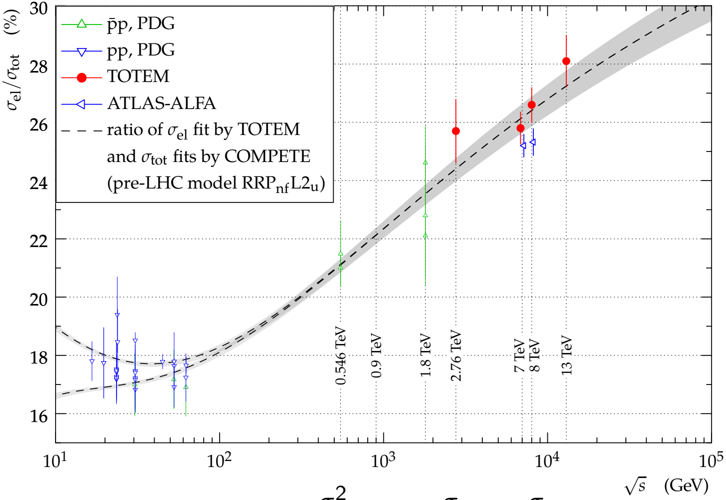
More complicated structure
at large $|t|$ values:
interference between contributing
amplitudes, e.g. Reggeons.

The elastic slope

$B_{\mathrm{el}} = 2\,(b_A + b_B + \alpha' \ln \bar{s}) = 9.2 + 0.5 \ln(s/4) \quad [\mathrm{GeV}^{-2}]$
undershoots at 7 TeV: 17.4 vs. data 19.8.



The elastic fraction



$$\sigma_{el} \approx \frac{\sigma_{tot}^2}{16\pi B_{el}} \Rightarrow \frac{\sigma_{el}}{\sigma_{tot}} \propto \frac{\sigma_{tot}}{B_{el}}$$

Increase has to slow down, e.g. by faster B_{el} growth!

Parametrization comments

Common with $c_0 + c_1 \ln \overline{s} + c_2 \ln^2 \overline{s}$ parametrizations for $\sigma_{\mathrm{tot}}(s)$, $\sigma_{\mathrm{el}}(s)$ and $B_{\mathrm{el}}(s)$, inspired by

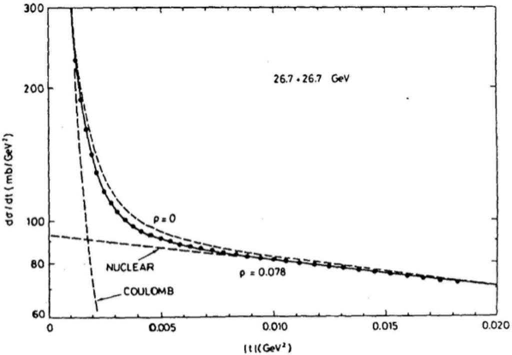
$$\mathrm{Froissart - Martin\ bound:} \quad \sigma_{\mathrm{tot}}(s) \leq \frac{\pi}{m_\pi^2} \ln^2 \overline{s}$$

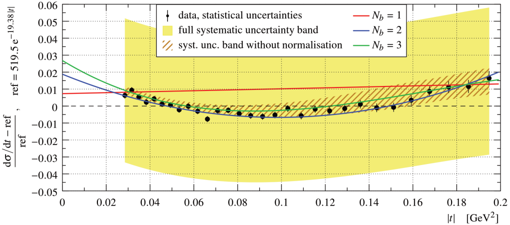
but nowhere near saturation at LHC, so $s^{0.08}$ also OK.

- Several Pomerons? Two-Pomeron models common! Higher intercept = "perturbative Pomeron" = QCD jets.
- Odderon: odd-parity exchange, could give $\sigma_{\mathrm{tot}}^{\mathrm{pp}}(s) > \sigma_{\mathrm{tot}}^{\mathrm{p\overline{p}}}(s)$.
- Multiple Reggeon trajectories.

$\Rightarrow$ Quite complicated fits to data, see e.g. Review of Particle Physics, pp. 590 – 597 in 2016 edition.

The Coulomb contribution



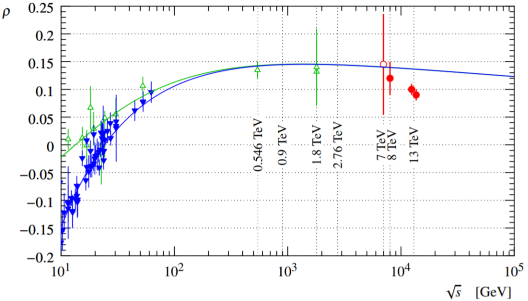


Coulomb dominates at small $|t|$: perfect luminometer if measurable.
However: unknown relative phase to ordinary "nuclear" (="QCD")

Further: "perfect" exponential is model, not theory.
Could have $B(t) = b_1 t + b_2 t^2 + \cdots$.
TOTEM observes $\sim 1\%$ deviations.

What if $\mathcal{M}$ not purely imaginary? Introduce

$$\rho(s) = \frac{\mathrm{Re}\,\mathcal{M}(s,0)}{\mathrm{Im}\,\mathcal{M}(s,0)} \quad \Rightarrow \quad |\mathcal{M}(s,0)|^2 = (1+\rho^2(s))\,\mathrm{Im}\,\mathcal{M}(s,0)$$



$\rho^2(s) \approx 0.04$ at LHC
$\Rightarrow$ often neglected

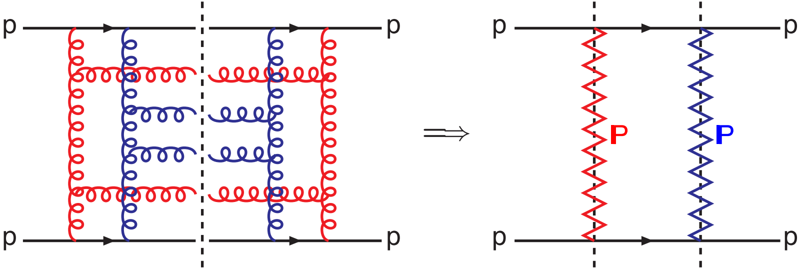
Recently unexpected small value observed by TOTEM.

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}(s)}{\mathrm{d}t} = (1+\rho^2(s))\,\frac{\sigma_{\mathrm{tot}}^2(s)}{16\pi}\,\exp(B_{\mathrm{el}}(s)\,t)$$

$$\sigma_{\mathrm{el}}(s) = (1+\rho^2(s))\,\frac{\sigma_{\mathrm{tot}}^2(s)}{16\pi\,B_{\mathrm{el}}(s)}$$

Cut Pomerons

Naively 1 $\mathbb{P} \approx 1$ MPI interaction, but in $p_\perp \to 0$ limit
$\Rightarrow$ longitudinal hadronization, multiparticle production
so multiple exchanges possible just like several MPIs

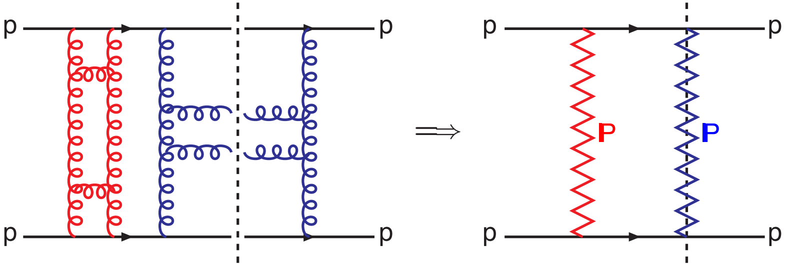


Physical cut: final state in squared Feynman graph.

Only one physical cut, duplicated for easier drawings.

Cut Pomeron: only one gluon line exchanged in physical final state, so coloured beam remnants and multiparticle production.

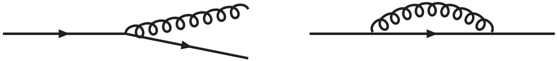
Also need virtual corrections to compensate real Pomerons:



Uncut Pomeron: a Pomeron exchange that leaves no explicit trace in final state, just like loops in standard perturbation theory.

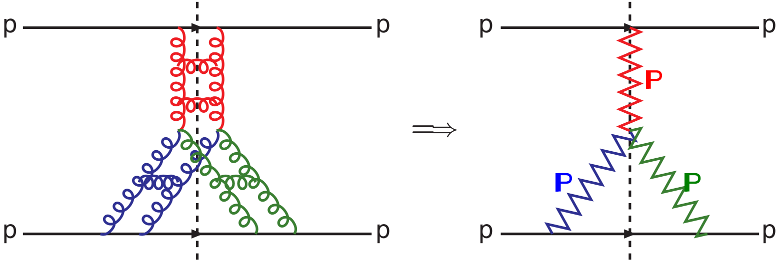
Restores unitarity: $\mathcal{P}_{\mathrm{cut}} + \mathcal{P}_{\mathrm{uncut}} = 1$;

just like real and virtual singularities cancel for matrix elements:



Minor issue: $p_{\perp} = 0$, so not ordering variable, but rapidity OK.

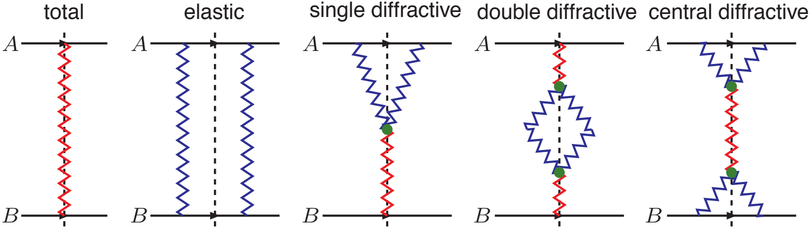
Gluon chains can split or fuse, giving diffraction:



Develops into a whole “Feynman diagram” framework:

- Pomeron propagator $G_{\mathbb{P}}(\overline{s}, t) = i\,\overline{s}^{\alpha(t)-1}$.
- $\beta_A(t) = \beta_A(0)\,\exp(b_A t)$, $A = \mathrm{p}, \mathrm{n}, \pi, \ldots$, strength of $AA\mathbb{P}$ vertex and A form factor.
- $g_{3\mathbb{P}}$ triple-Pomeron vertex.
- ($G_{\mathbb{R}}(\overline{s}, t)$ and $g_{\mathbb{R}\mathbb{R}\mathbb{P}}$ for Reggeons.)

Differential cross section expressions



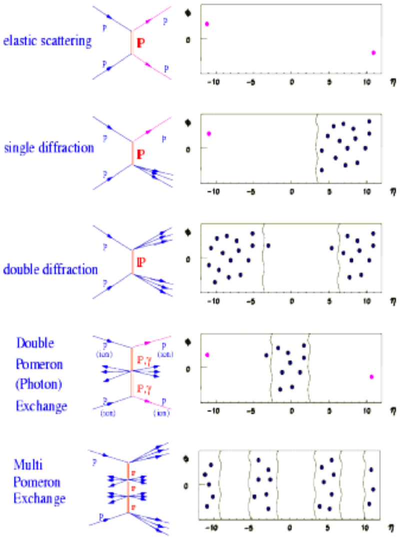
$$\sigma_{\mathrm{tot}}^{AB} = \beta_A(0)\,\beta_B(0)\,\mathrm{Im}\,G_{\mathbb{P}}(s/s_0, 0)$$

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}^{AB}}{\mathrm{d}t} = \frac{1}{16\pi}\,\beta_A^2(t)\,\beta_B^2(t)\,|G_{\mathbb{P}}(s/s_0, t)|^2$$

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}}^{AB\to AX}}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{1}{16\pi\,M^2}\,g_{3\mathbb{P}}\,\beta_A^2(t)\,\beta_B(0)|G_{\mathbb{P}}(s/M^2, t)|^2\,\mathrm{Im}\,G(M^2/s_0, 0)$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}^{AB\to X_1X_2}}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{1}{16\pi\,M_1^2\,M_2^2}\,g_{3\mathbb{P}}^2\,\beta_A(0)\,\beta_B(0)\,|G_{\mathbb{P}}(ss_0/(M_1^2M_2^2), t)|^2 \times \mathrm{Im}\,G(M_1^2/s_0, 0)\,\mathrm{Im}\,G(M_2^2/s_0, 0)$$

Event-type properties



- Phase space for diffractive masses and rapidity gaps roughly like $\mathrm{d}M^2/M^2 = \mathrm{d}y$, i.e. flat in rapidity.
- Extra divergence $\int_{s_0}^{s} \mathrm{d}M^2/M^2 = \log(s/s_0)$ means σ_{sd} grow faster that σ_{tot}, and σ_{dd} even faster.
- Plausibly sequence of increasingly complicated topologies.
- $B_{\mathrm{el}}(s) > B_{\mathrm{sd}}(s, M^2) > B_{\mathrm{dd}}(s, M_1^2, M_2^2)$

Single diffractive kinematics

$$
\begin{aligned}
\xi = \frac{M_X^2}{s} \quad &\Rightarrow \quad x_{\mathrm{p}} = \frac{2E_{\mathrm{p}}}{E_{\mathrm{cm}}} = 1 - \xi \\
\mathrm{d}(\log M_X^2) = \frac{\mathrm{d}M_X^2}{M_X^2} \quad &= \quad \frac{\mathrm{d}\xi}{\xi} = \mathrm{d}(\log \xi) \\
\Delta y_{\mathrm{tot}} \quad &\approx \quad 2\log\left(\frac{(E+p_z)_{\mathrm{p}}}{m_{\mathrm{p}}}\right) = \log\frac{s}{m_{\mathrm{p}}^2} \\
\Delta y_X \quad &\approx \quad \log\frac{M_X^2}{m_{\mathrm{p}}^2} \\
\Delta y_{\mathrm{gap}} \approx \Delta y_{\mathrm{tot}} - \Delta y_X \quad &\approx \quad \log\frac{s}{M_X^2} = \log\frac{1}{\xi} = -\log\xi
\end{aligned}
$$

Experimentally: spurious “false” gaps if $\Delta y_{\mathrm{gap}} \leq 3 \Rightarrow \xi \geq 0.05$.
$B_{\mathrm{sd}} \sim 10$ GeV$^{-2} \Rightarrow \langle p_{\perp}^2 \rangle \approx \langle |t| \rangle \approx 0.1$ GeV^2.
$E_{\mathrm{cm}} = 7$ TeV$\Rightarrow \langle \theta \rangle \approx 0.35/3500 = 10^{-4}$ so need Roman pots.

Rise of diffractive cross section

Naive steep rise of all diffractive topologies problematic.

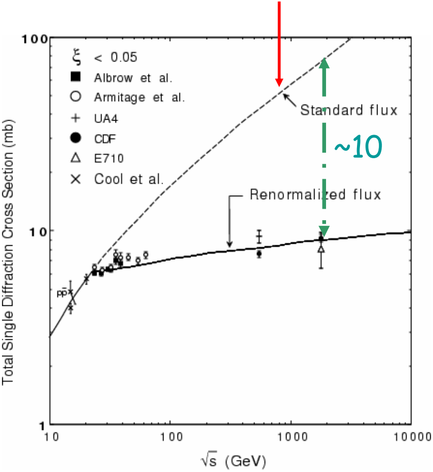
Goulianos: rescale Pomeron flux by hand:

- Unitarity problem:
  With factorization and std pomeron flux σ_{SD} exceeds σ_T at $\sqrt{s} \approx 2$ TeV.

- Renormalization:
  normalize the pomeron flux to unity

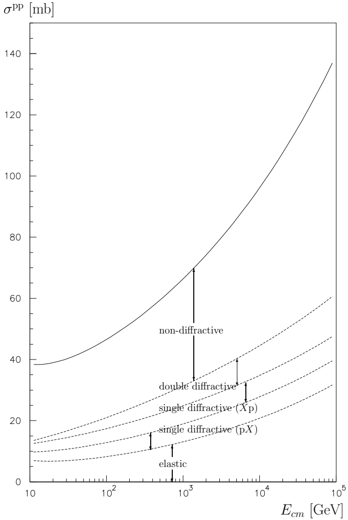
KG, PLB 358 (1995) 379

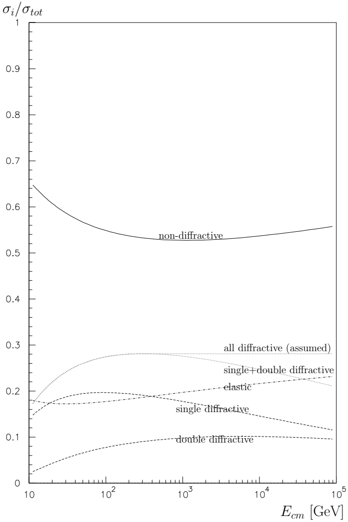
$$\boxed{\int_{\xi_{min}}^{0.1} \int_{t=-\infty}^{0} f_{IP/p}(t,\xi)\, d\xi\, dt = 1}$$



Cross section fractions

Schuler&Sjöstrand 1993: patch up for finite asymptotic ratios:





Ongoing work with Christine for new solution.

Total unitarization

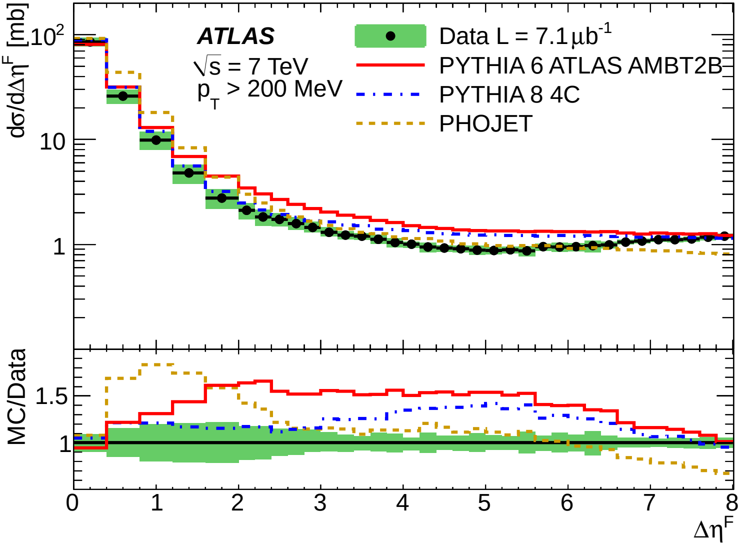
DTUJET/DPMJET/PHOJET: eikonalization of four components:
$i = s$: soft Pomerons $\Leftrightarrow$ normal nondiffractive exchange
$i = h$: hard cross section $\Leftrightarrow$ QCD jets
$i = t$: triple-Pomeron processes $\Leftrightarrow$ single diffraction
$i = c$: cut loops $\Leftrightarrow$ double diffraction

$$\chi_i(b,s) = \frac{\sigma_i(s)}{8\pi B_i(s)} \exp\left(-\frac{b^2}{4B_i(s)}\right) \quad \text{with} \quad \int 2\chi_i(b,s)\,\mathrm{d}^2 b = \sigma_i(s)$$

$$\begin{aligned}\sigma(n_s, n_h, n_t, n_c, b, s) &= \frac{(2\chi_s)^{n_s}}{n_s!}\,\frac{(2\chi_h)^{n_h}}{n_h!}\,\frac{(2\chi_t)^{n_t}}{n_t!}\,\frac{(2\chi_c)^{n_c}}{n_c!} \\ &\times \exp\left(-2\sum_i \chi_i(b,s)\right)\end{aligned}$$

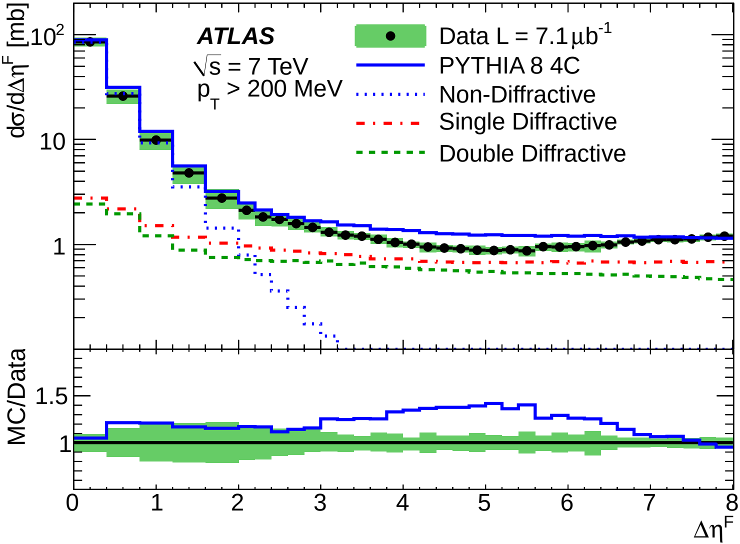
Soft+hard interactions may overlay single/double diffraction and fill up rapidity gaps. $\Rightarrow$ Diffraction killed for central collisions but survives for peripheral ones.

Measured gap size



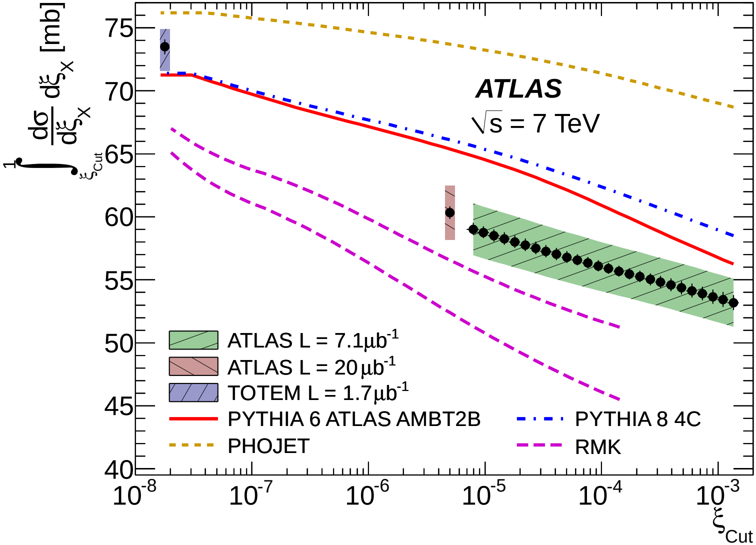
PYTHIA 8 tune 4C has reduced diffraction, but not enough.

Gaps by subprocess



Non-diffractive fine, but wrong gap spectrum for diffraction.

Diffractive mass dependence

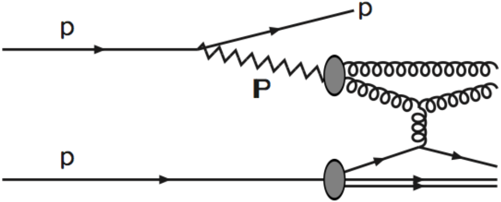


Need more low-mass enhancement than already in PYTHIA.

The Ingelman–Schlein model

Regge theory predicts/parametrizes rate of diffractive interactions, but does not tell what diffractive events look like.

Ingelman-Schlein (1984): Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) $\times$ ($\mathbb{P}\mathrm{p}$ collision)

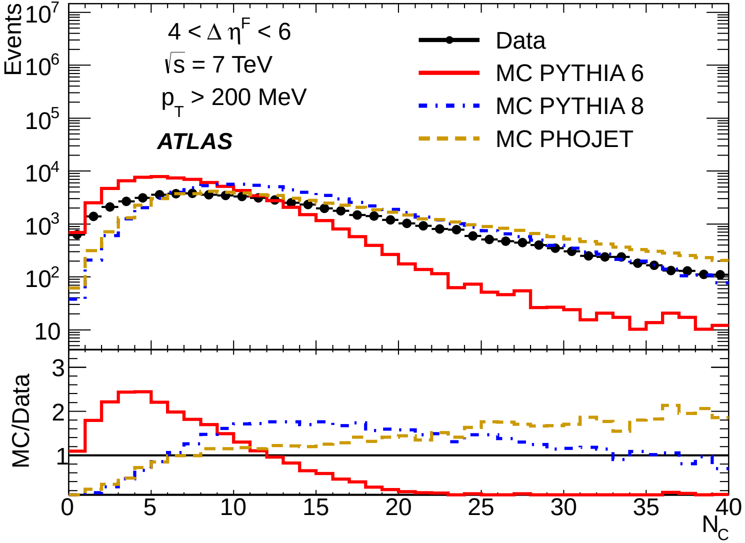


$\mathrm{pp} \to \mathrm{p}X$

$\mathbb{P}\mathrm{p}$ subcollision just like a pp one,
with (semi)hard interaction, MPIs, ISR, FSR, beam remnants,
only with a different $\mathbb{P}$ PDF.

$\mathbb{P}$ PDF mainly determined from HERA data.
$\mathbb{P}$ flux and $\mathbb{P}$ PDF not separately determined.
$\mathbb{P}$ not real particle so not normalized to unit momentum sum (!?).

Multiplicity in diffractive events



PYTHIA 6 lacks MPI, ISR, FSR in diffraction, so undershoots.

Hard diffraction

Diffractive events can contain high-$p_\perp$ jets:

$$\sigma = \int \mathrm{d}x_{\mathbb{P}}\, f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \int \mathrm{d}x_i\, f_{i/\mathbb{P}}(x_i', Q^2)\, \mathrm{d}x_j \int f_{j/\mathrm{p}}(x_j, Q^2) \int \mathrm{d}\hat{\sigma}_{ij}(\hat{s})$$

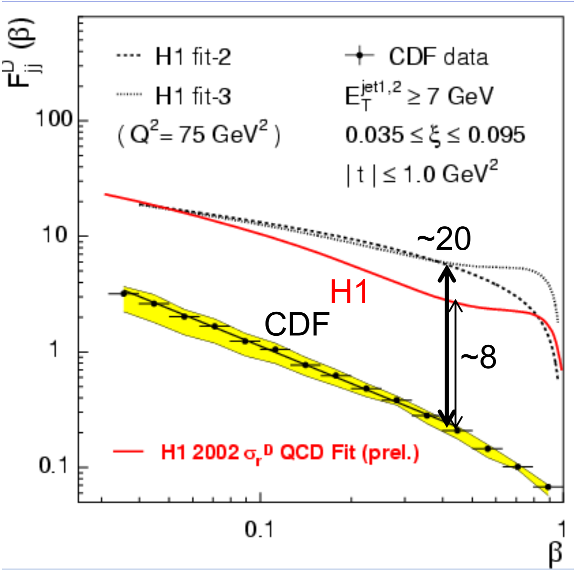
with $M_X^2 = x_{\mathbb{P}} s = \xi s$ and $\hat{s} = x_i' x_j M_X^2 = \beta x_j M_X^2$,
i.e. $x_i = x_{\mathbb{P}} x_i' = \xi\beta$.

$$f_{\mathbb{P}}(x_{\mathbb{P}}, t) \sim \frac{1}{x_{\mathbb{P}}} \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}M_X^2} \sim \frac{1}{M_X^2} \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}y_{\mathrm{gap}}} \sim \mathrm{constant}$$

Many issues, e.g.:

1. imperfect factorization
   $f_{i/\mathrm{p}}(x_{\mathbb{P}}, t, x_i, Q^2) = f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)\, f_{i/\mathbb{P}}(x_i, Q^2)$
2. poor knowledge of $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)$ and $f_{i/\mathbb{P}}(x_i, Q^2)$
3. parameters of multiple interactions framework
4. multipomeron topologies, . . .

Non-universality



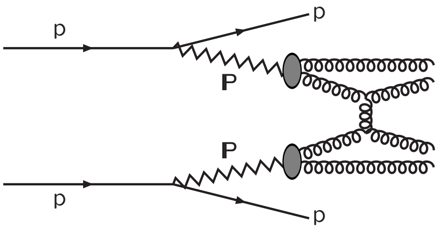
Diffractive dijet production.

HERA diffraction (flux and PDF) overpredicts Tevatron one by factor ~ 8.

Could be explained by MPI filling up and killing gaps (MPI not present in DIS at HERA).

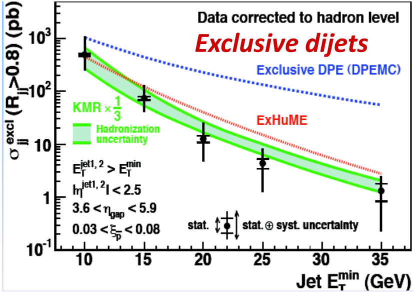
Central diffraction

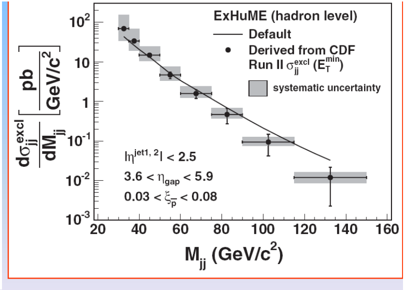
Can apply Ingelman-Schlein also to double diffraction or central diffraction:



Extreme case is exclusive central diffraction: no Pomeron beam remnants.

Observed e.g. as exclusive χ_c or exclusive (?) jets:



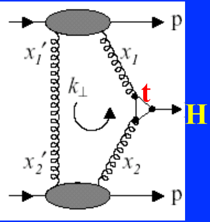


Central Higgs production (Mike Albrow)

Higgs has vacuum quantum numbers, vacuum has Higgs field.
So pp → p+H+p is possible ***in principle***.
Allowed states: $\boxed{\mathrm{I}\ J^{PC} = 0\ \mathrm{even}^{++}}$

J >= 2 strongly suppressed at small |t|

Process is gg → H through t-loop as usual
with another g-exchange to cancel color
and even leave p's in ground state.
If we measure p's (4-vectors):

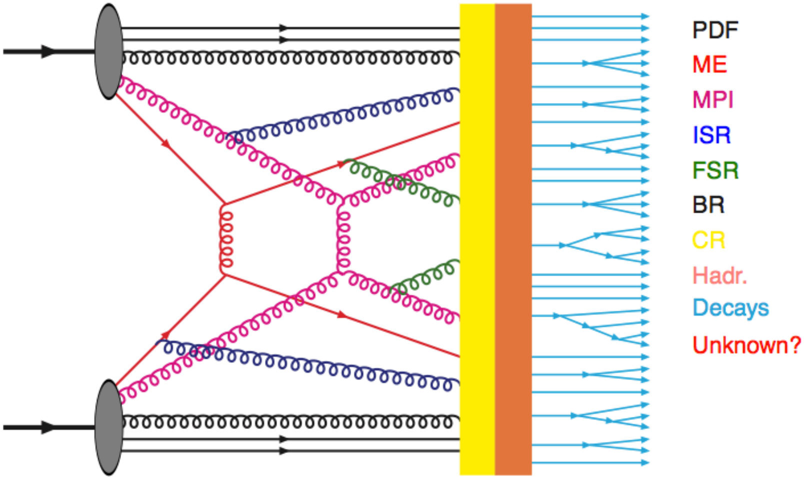


$$\mathrm{M_{CEN}} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2} \longrightarrow \boxed{\sigma(M_H) \approx 2\ \mathrm{GeV\ per\ event}}$$

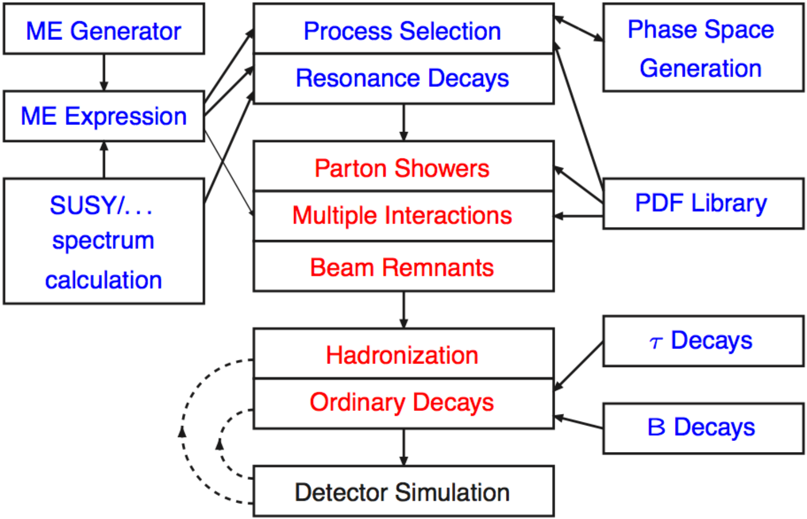
Even for $\mathrm{H} \to \mathrm{W^+W^-} \to \mathrm{l^\pm \nu JJ}$!

Cross section calculations a topic of some debate.
Exclusive $\mathrm{b\overline{b}}$ production non-negligible background to $\mathrm{H} \to \mathrm{b\overline{b}}$.

Generator physics



Combining tasks



Need standardized interfaces: see next!

PDG Particle Codes – 1

A. Fundamental objects

1	d	11	e^-	21	g				
2	u	12	ν_e	22	γ	32	Z'^0		
3	s	13	μ^-	23	Z^0	33	Z''^0		
4	c	14	ν_μ	24	W^+	34	W'^+		
5	b	15	τ^-	25	h^0	35	H^0	37	H^+
6	t	16	ν_τ			36	A^0	39	G_{raviton}

add − sign for antiparticle, where appropriate

+ a wide range of exotica, e.g.

SUSY	1000021	$\tilde{g}$
Technicolor	3000113	ρ_{TC}
compositeness	4000005	b^*
extra dimensions	5100039	G^*_{raviton}

PDG Particle Codes – 2

B. Mesons

$100\,|q_1| + 10\,|q_2| + (2s+1)$ with $|q_1| \geq |q_2|$

particle if "heaviest" quark u, $\overline{\mathrm{s}}$, c, $\overline{\mathrm{b}}$; else antiparticle

111	π^0	311	K^0	130	K^0_L	421	D^0
211	π^+	321	K^+	310	K^0_S	431	D^+_s
221	η^0	331	η'^0	411	D^+	443	J/ψ

C. Baryons

$1000\,q_1 + 100\,q_2 + 10\,q_3 + (2s+1)$

with $q_1 \geq q_2 \geq q_3$, or Λ-like $q_1 \geq q_3 \geq q_2$

2112	n	3122	Λ^0	2224	Δ^{++}	3214	Σ^{*0}
2212	p	3212	Σ^0	1114	Δ^-	3334	Ω^-

D. Diquarks

$1000\,q_1 + 100\,q_2 + (2s+1)$ with $q_1 \geq q_2$

1103	uu_1	2101	ud_0	2103	ud_3	2203	dd_3

Les Houches Accord

Context: ME generator $\rightarrow$ PS/UE/hadronization

Transfer info on processes, cross sections, parton-leven events, . . .

LHA: Les Houches Accord (2001)
formulated in terms of two Fortran commonblocks
1) overall run information for initialization
2) parton configuration one event at a time

LHEF: Les Houches Event File(s) (2006)
same information, but stored as a single plaintext file.
$+$ language-independent, cleaner separation, reuse same file
$-$ large files if many events

LHEF3: Les Houches Event File(s) (2014)
backwards compatible, but adds further information,
notably for matching/merging: event weights, event groups,. . .

Other interfaces

- SLHA — SUSU Les Houches Accord: file with info on SUSY or other BSM model (+top, Higgs, W/Z): parameters, masses, mixing matrices, branching ratios, ... Output from spectrum calculator, input to event generator.
- LHAPDF: uniform interface to PDF parametrizations. LHAPDF5 drawback: in Fortran; bloated! LHAPDF6: in C++, standard for LHC (but some gaps)
- HepMC: output of complete generated events (intermediate stages and final state with hundreds of particles) for subsequent detector simulation or analysis
- Binoth LHA: provide one-loop virtual corrections
- FeynRules: input of Lagrangian and output of Feynman rules, to be used by matrix element generators
- ProMC: event record in highly compressed format
- . . .

MCnet

⋆ “Trade Union” of (QCD) Event Generator developers ⋆

Main projects:
HERWIG
SHERPA
PYTHIA
MadGraph
Rivet

Also: PROFESSOR, ARIADNE, DIPSY, HEJ, VINCIA, DIRE, . . .
(Manchester, Durham, Glasgow, Göttingen, Karlsruhe,
Louvain, Lund, UC London
+ associated: CERN, Monash, FNAL, SLAC, Vienna, . . .).

Marie Curie training network 2007–2010, 2013–2016, 2017–2021.
EU money for graduate students, short-terms studentships,
travel, meetings, summer schools.

HERWIG, PYTHIA and SHERPA offer convenient frameworks for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):
- originated in hadronization studies: the Lund string
- leading in development of MPI for MB/UE
- pragmatic attitude to showers & matching

HERWIG (successor to EARWIG, begun in 1984):
- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- spin correlations in decays; MatchBox match&merge

SHERPA (APACIC++/AMEGIC++, begun in 2000):
- own matrix-element calculator/generator
- extensive machinery for matching and merging
- hadronization & min-bias physics lower priority

PYTHIA & HERWIG originally in Fortran, now all C++

Other special-purpose programs – examples

- ARIADNE: dipole shower.
- DIPSY: dipole-based picture of pp, pA and AA collisions.
- HEJ: BFKL-inspired approximate multijet matrix elements.
- VINCIA: antenna shower, aims towards NLL.
- DIRE: dipole shower, aims towards NLL.
- EVTGEN: B decays, with detailed handling of interference, polarization and *CP*-violation effects.
- TAUOLA, τ decays, with polarization effects (correlated in pairs).
- PHOTOS: photon emission in decays of (electroweak) resonances or hadrons.
- . . .

Comparison of tree-level tools

	Models	$2 \to n$	Ampl.	Integ.	public?	lang.
ALPGEN	SM	$n = 8$	rec.	Multi	yes	Fortran
AMEGIC++	SM,MSSM,ADD	$n = 6$	hel.	Multi	yes	C++
COMIX	SM	$n = 8$	rec.	Multi	yes	C++
COMPHEP	SM,MSSM	$n = 4$	trace	1Channel	yes	C
HELAC	SM	$n = 8$	rec.	Multi	yes	Fortran
MADEVENT	SM,MSSM,UED	$n = 6$	hel.	Multi	yes	Python/Fortran
WHIZARD	SM,MSSM,LH	$n = 8$	rec.	Multi	yes	O'Caml

Specific solutions

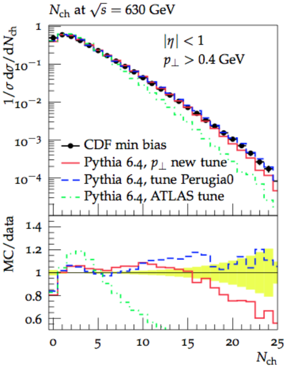
- For a long time only process-specific codes, e.g.:
  - NLOJET++ (jets only),
  - VBFNLO (VBF-type processes),
  - and MCFM (the interesting rest)
- Recently: (semi-)automated codes:
  - BLACKHAT +SHERPA
  - HELAC +CUTTOOLS
  - ROCKET
  - MADLOOP

Also: MadGraph5_aMC@NLO first truly general-purpose NLO.

Rivet

Tool for generator validation and comparisons with data:

- Analyses can be implemented in Rivet and applied to MC
- Uses HepMC ⇒ generator-independent, perfect for comparisons
- Many key analyses are already implemented; many more to come.
- Important for keeping your data alive: Publish your numbers corrected to hadron level and implement your analysis in Rivet.



1. Choosing parameters

Pick the parameters you want to tune:

- Tune everything that is important.
- But remember: Each additional parameter adds one dimension to the parameter space.

Define parameter intervals:

- Make the interval large enough so that the result will not be outside.
- But remember: Cutting down 10 intervals by 10 % shrinks the volume of the parameter space by 2/3.

2. Predict the Monte Carlo

Get a bin by bin prediction for the MC response as function of the parameter set $\vec{p} = (p_1, p_2, \ldots, p_n)$.

Using a second order polynomial takes the correlations between the parameters into account:

$$X_{\mathrm{MC}}(p_1, p_2, \ldots, p_n) =$$
$$A_0 + \sum_{i=1}^{n} B_i p_i + \sum_{i=1}^{n} C_i p_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} D_{ij} p_i p_j + \cdots$$

Requires $\mathcal{O}(n^2)$ points *at random* inside allowed parameter volume

3. Fit the prediction to data

Having A_0, B_i, C_i and D_{ij} we can predict the MC response for any set of parameters very fast. This prediction can be fitted to data, minimising the χ^2:

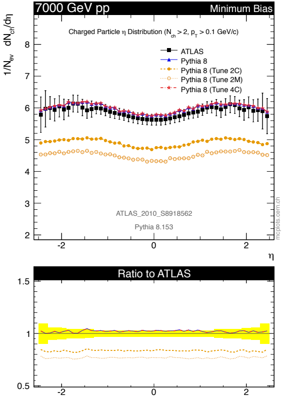
$$\chi^2(\vec{p}) = \sum_{\text{observables}} \sum_{\text{bins}} \left(\frac{X_{\text{data}} - X_{\text{MC}}(\vec{p})}{\sigma_{\text{data}}} \right)^2$$

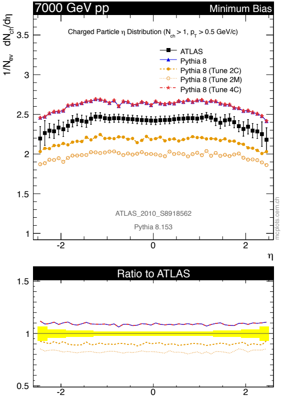
Include all the relevant data distributions in the fit!

This fit only takes seconds (as compared to days or weeks for a brute force approach).

Repository of comparisons between various tunes and data, mainly based on RIVET for data analysis, see `http://mcplots.cern.ch/`.
Part of the LHC@home 2.0 platform for home computer participation.

Generator	Version
alpgenherwigjimmy	
alpgenpythia6	
herwig++	
herwig++powheg	
pythia6	
pythia8	
sherpa	
vincia	





Tuning (Peter Skands)

3 Kinds of
Tuning

1. Fragmentation Tuning

Non-perturbative: hadronization modeling & parameters

Perturbative: jet radiation, jet broadening, jet structure

2. Initial-State Tuning

Non-perturbative: PDFs, primordial k_T

Perturbative: initial-state radiation, initial-final interference

3. Underlying-Event & Min-Bias Tuning

Non-perturbative: Multi-parton PDFs, Color (re)connections, collective effects, impact parameter dependence, ...

Perturbative: Multi-parton interactions, rescattering

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PYTHIA 8 tuning

Currently 34 tunes available:

- 6 internal MB+UE tunes, leading up to 4C and 4Cx.
- 8 ATLAS MB or UE tunes, based on 4C or 4Cx.
- 2 CMS UE tunes based on 4C.
- 1 Monash 2013 tune.
- 14 ATLAS A14 UE tunes based on Monash 2013, whereof 4 central with different PDF sets, and 2×5 eigentune variations up/down.
- 1 CMS UE tune based on Monash 2013.
- 2 special-purpose tunes.

To note:

- Even ambitious tunes, like ATLAS A14, with ~ 10 parameters in Professor approach, start from "by hand" tunes.
- Split into UE and MB tunes mainly by user community; physics conflict beyond reasonable levels not established.