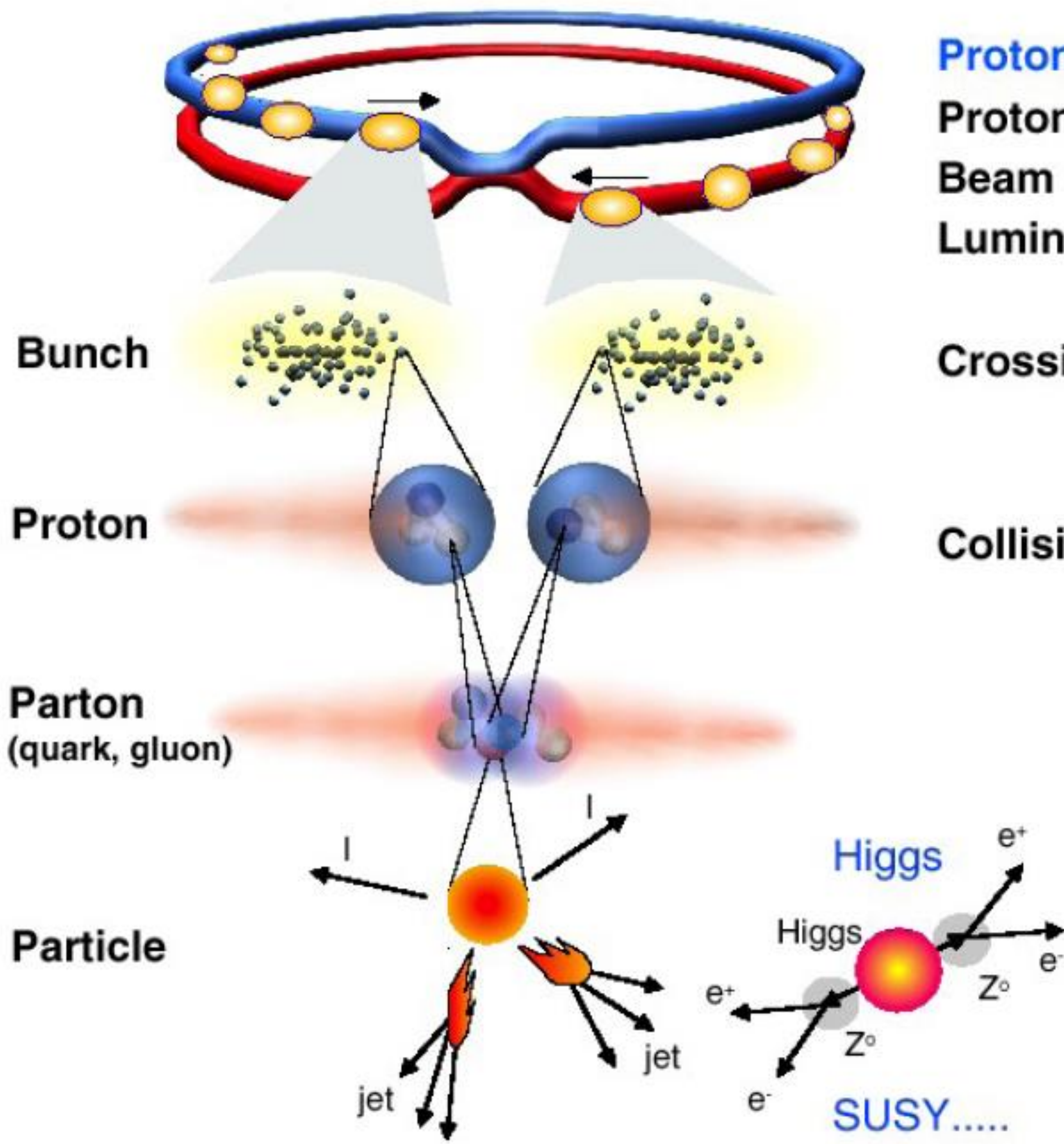
Collisions at LHC

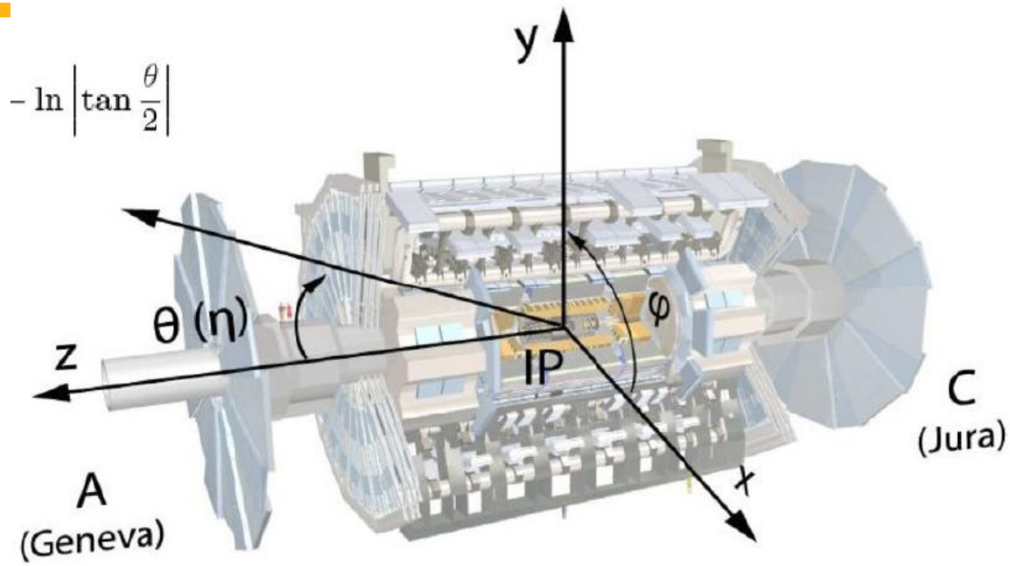


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

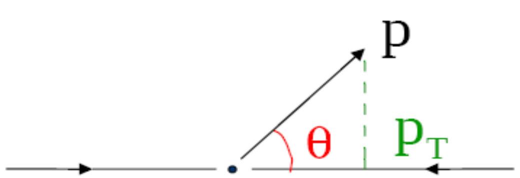
Selection of 1 in 10,000,000,000,000

ATLAS Detector

THE ATLAS DETECTOR IS REALLY BIG!



- Length : ~ 46 m
- Radius : ~ 12 m
- Weight : ~ 7000 tons
- $\sim 10^8$ electronic channels
- 3000 km of cables



Transverse momentum

(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

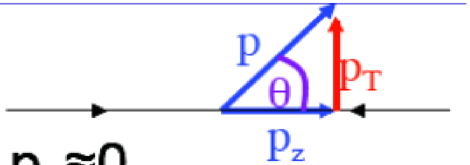
Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

$\theta = 170^\circ \rightarrow \eta \cong -2.4$

Kinematical variables



- **Transverse momentum, p_T**
  - Particles that escape detection ($\theta<3^o$) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$
    - **Very useful variable!**
- **Longitudinal momentum and energy, p_z and E**
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - **Not a useful variable**
- **Polar angle θ**
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{4\pi\, \sigma_x\, \sigma_y}$$

LHC: f=c/26.7 km

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Efficiency: optimized by experimentalist

Cross section σ: Given by Nature (calc. by theorists)

17 **Ability to observe something depends on N_{obs}**

Units of cross-sections

- Originally introduced to express areas of nuclei and nuclear reactions.

Conversion to SI units

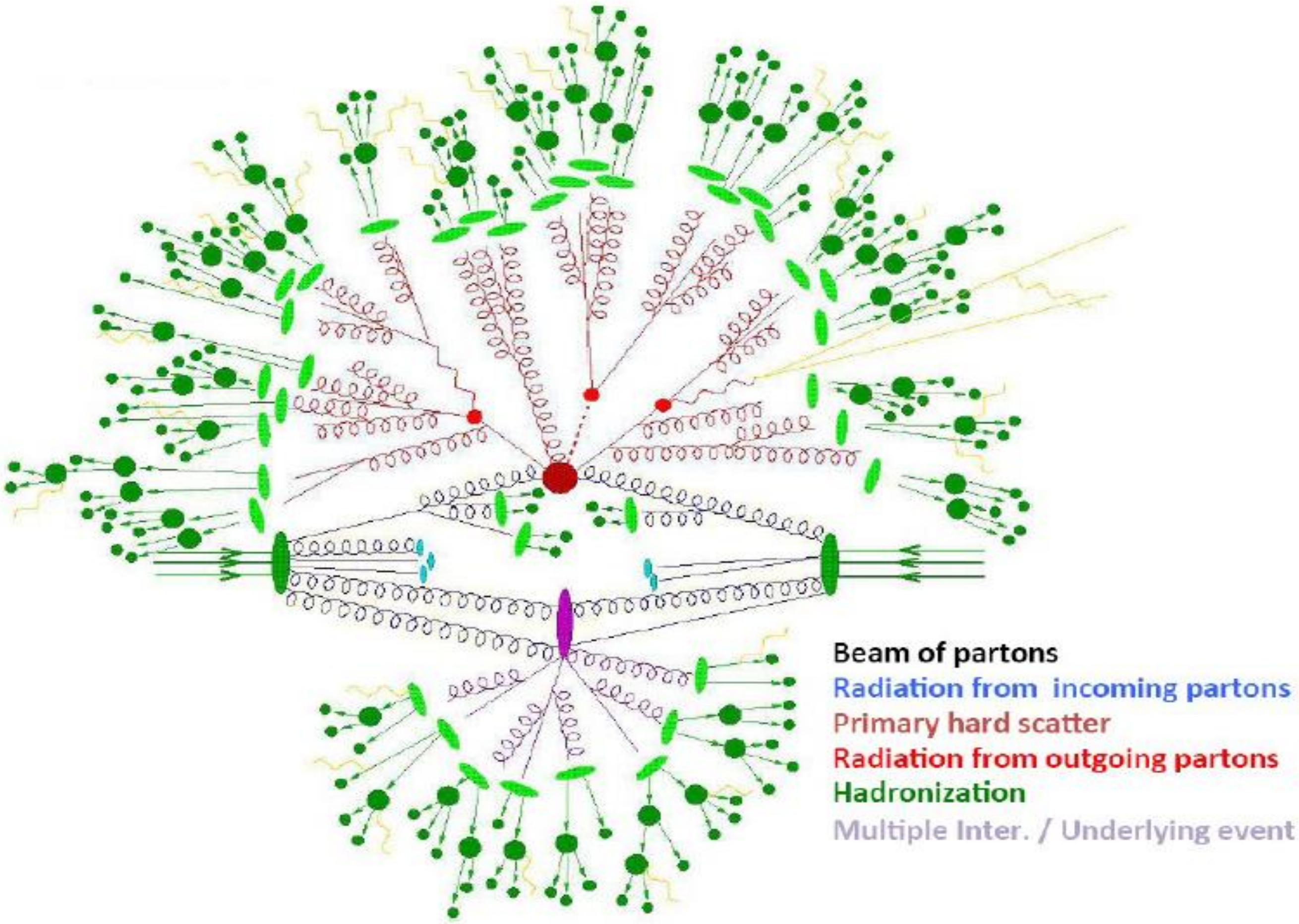
Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	µb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb [6][7]	10^{-52}	10^{-48}

- "inverse femtobarn (fb^{-1})": is a measurement of particle collision events per femtobarn of target cross-section (area) and is conventional unit for integrated luminosity
- "integrated luminosity: an indication of particle collider productivity

eg. Tevatron: 1fb^{-1} in 4 years

ATLAS: 5 fb^{-1} in 2011

Typical pp collision



Calculating a cross-section

- Cross-section is convolution of pdf's and matrix element

Physical cross section

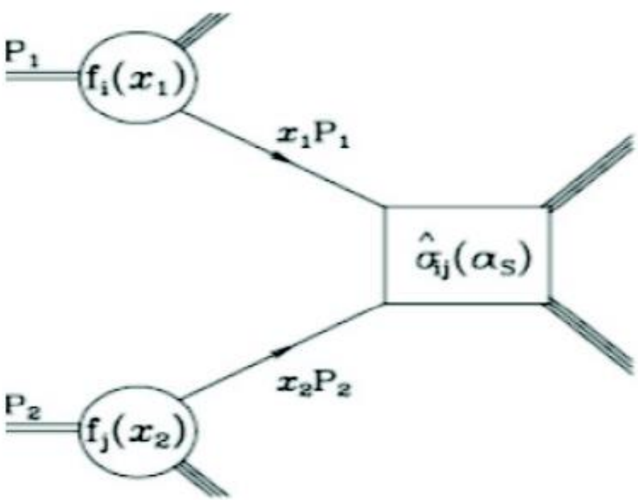
Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F) f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

Factorization scale μ_F

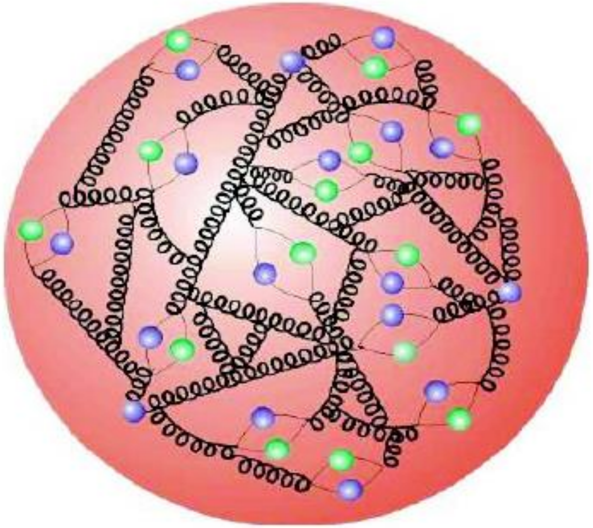
Short distance cross section, calculated as a perturbation series in α_S



- Calculations are done in perturbative QCD
  - Possible thanks to factorisation of hard ME and pdf's
    - Can be treated independently
  - Strong couplings (α_s) is large
    - Higher orders needed
    - Calculations complicated

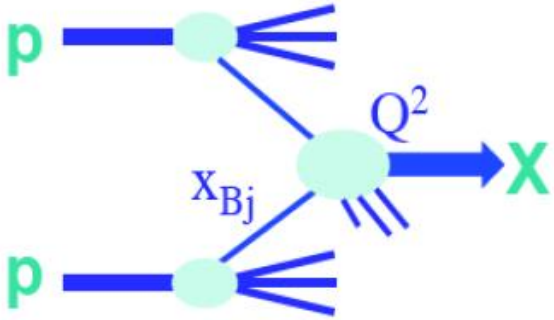
The proton composition

- It's complicated:
  - Valence quarks, gluons, sea quarks
- Exact mixture depends on:
  - Q^2: ~ $(M^2+p_T^2)$
  - Bjorked-x: fraction of momentum caried by a parton



$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

$$M_X = \sqrt{\hat{s}}$$



Parton kinematics

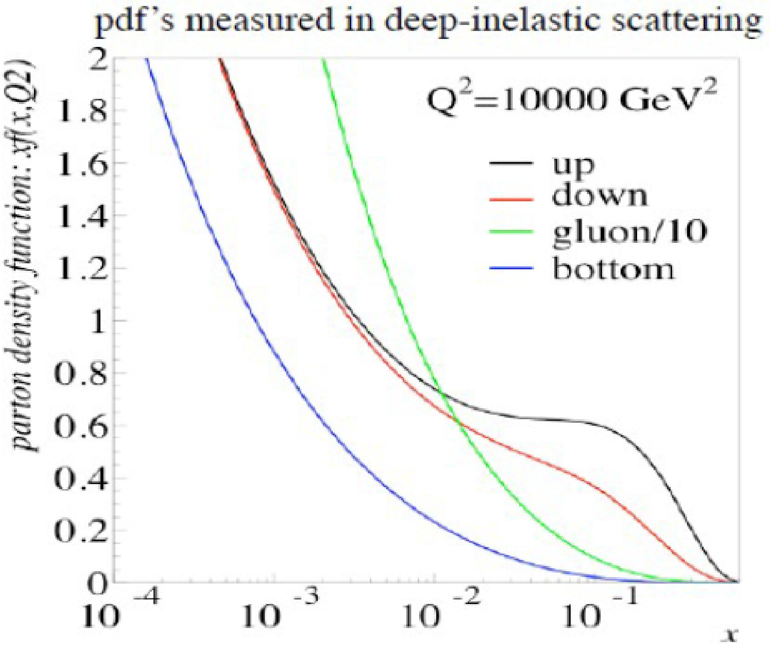
- Examples:

Higgs: M~100 GeV

- LHC: <xp> = 100/7000 ~ 0.014

Gluino: M ~ 1TeV

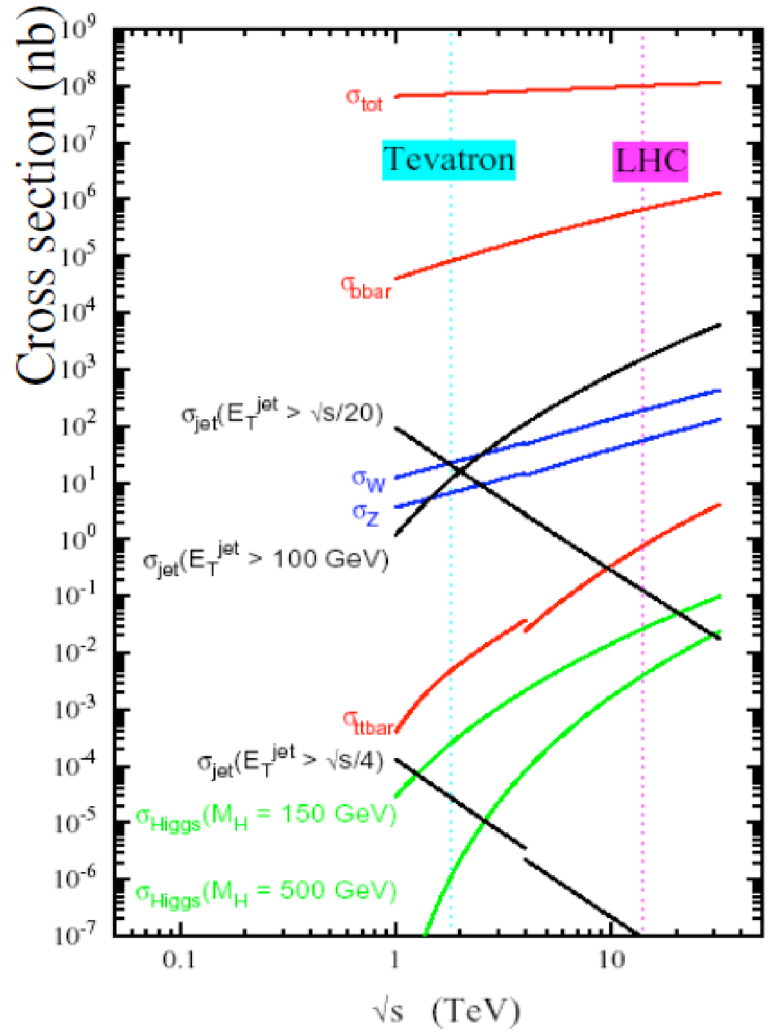
- LHC: <xp> = 1000/7000 ~ 0.14



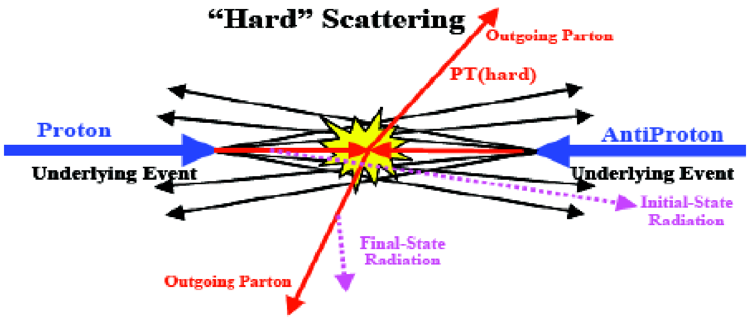
- Partons densities rise dramatically towards low x
  - Larger cross-sections at LHC than in previous experiments (Tevatron).

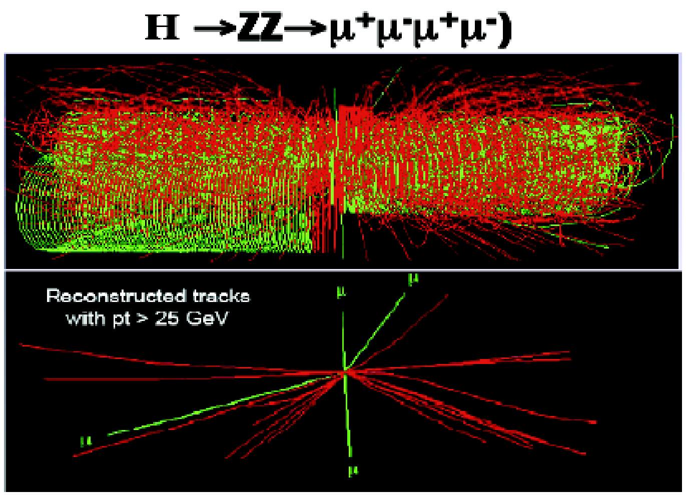
Cross-sections at LHC

- A lot more "uninteresting" than "interesting" processes at design luminosity (L = 10^{34}cm^{-2}s^{-1})
  - Any event: 10^9/sec
  - W boson: 150/sec
  - Top quark: 8/sec
  - Higgs (125GeV): 0.2/sec
- Interesting events gets selected:
  I. trigger (decision!)
  II. physics analysis (selection)



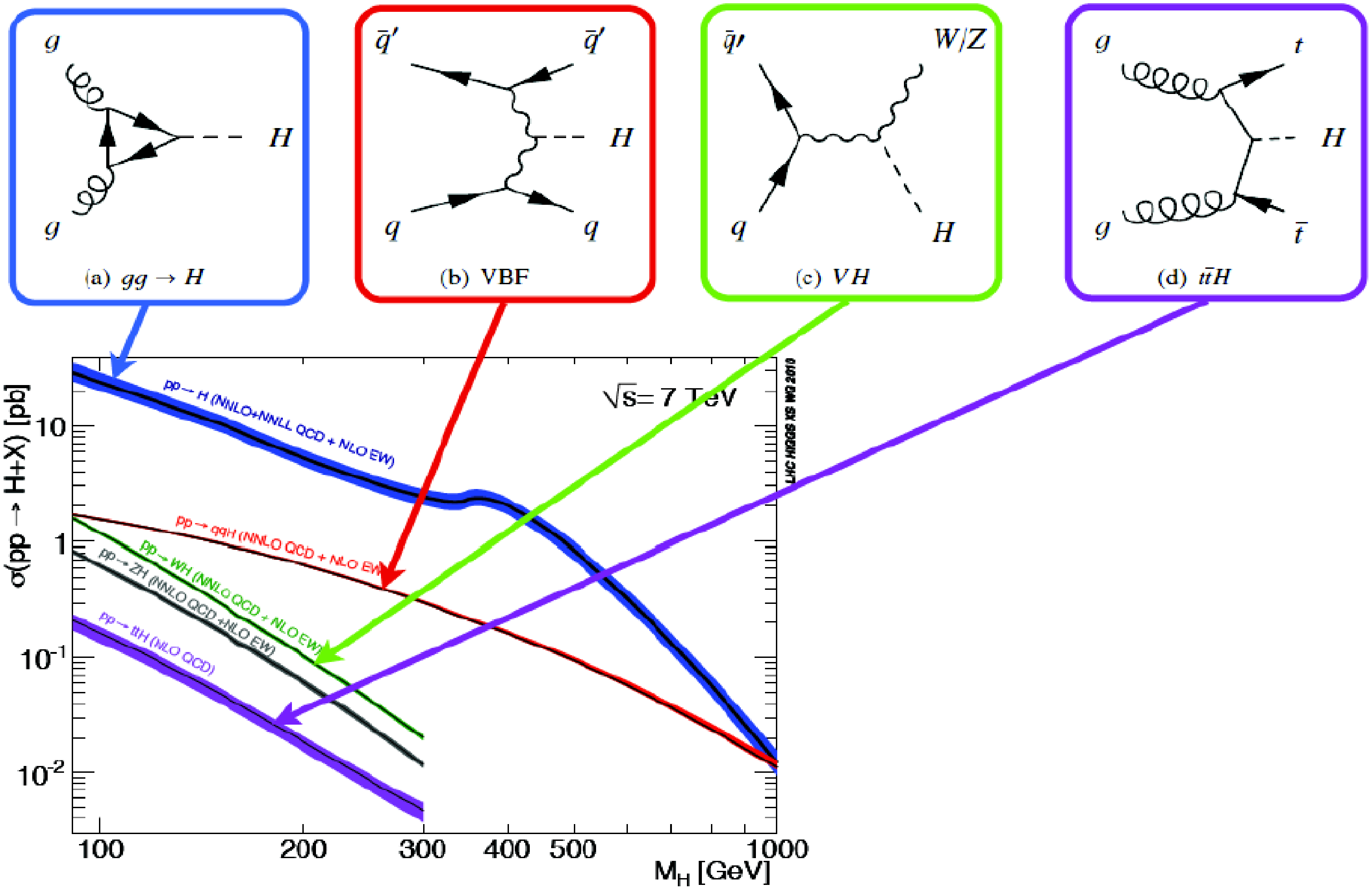
Every event is complicated





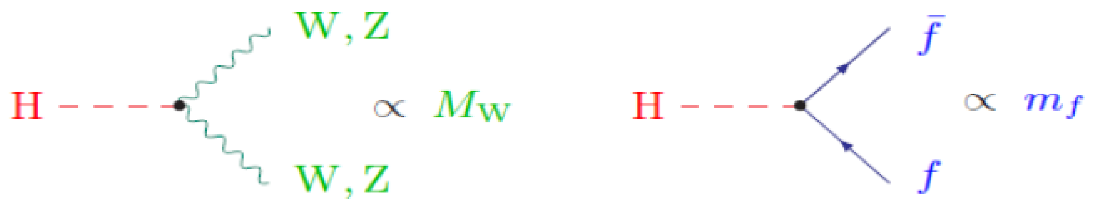
- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Additional pp interactions
  - LHC: ~1.5 (~23 at design values) → Even >30 with present operation conditions
  - Tevatron: ~10
- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0

SM Higgs production at LHC



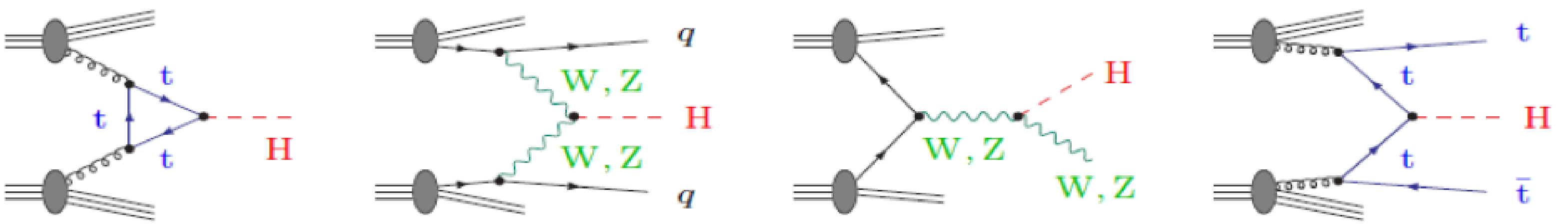
SM Higgs production and decays

Higgs bosons couple proportional to particle masses:



$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

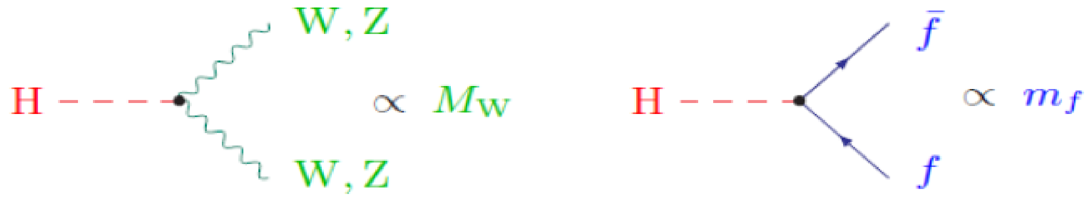
Production at hadron colliders ($p\bar{p}/pp$):



Decay channels for Higgs bosons of moderate mass ($M_H \lesssim 300\,\mathrm{GeV}$):

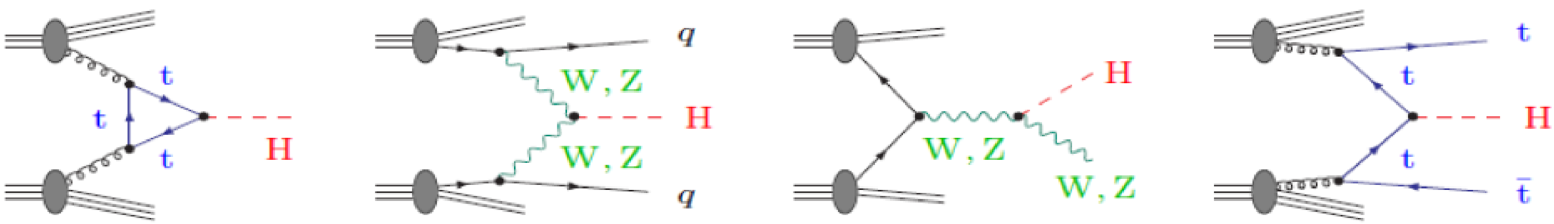
SM Higgs production and decays

Higgs bosons couple proportional to particle masses:



⇒ Higgs production via couplings to W/Z bosons or top-quarks

Production at hadron colliders ($p\bar{p}/pp$):

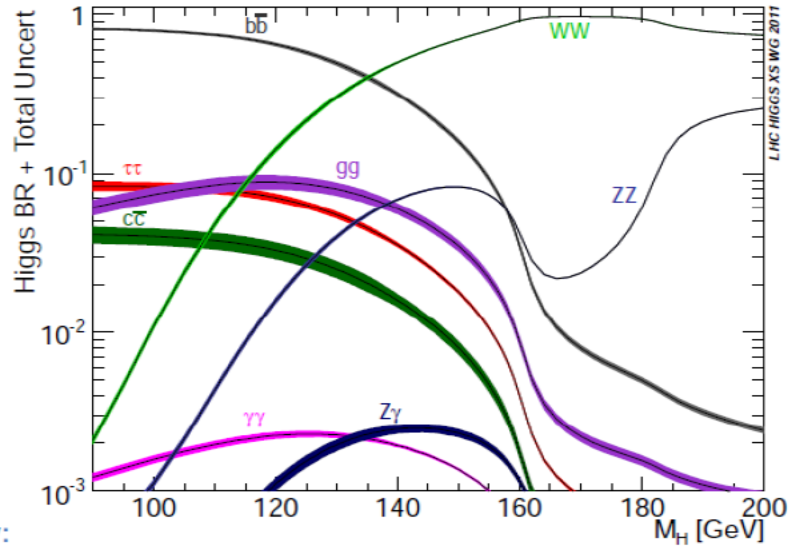


Decay channels for Higgs bosons of moderate mass ($M_H \lesssim 300\,\text{GeV}$):

SM Higgs production and decays

At $L = 7\times10^{33}$ $s^{-1}cm^{-2}$ and 8 TeV *pp* collisions, 560 Higgs bosons of mass 125 GeV ($\sigma_{pp\to H}$ = 22.3 pb) are produced in ATLAS and CMS per hour

Or: every 45 min. 1 $H\to\gamma\gamma$, need ~2 typical 160 pb^{-1} fills to produced one $H\to 4l$ ($l=e/\mu$)



Parametric + theoretical uncertainty:

M_H[GeV]	$H\to b\bar{b}$	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$	WW	ZZ
120	3%	6%	12%	10%	5%	5%	5%
150	4%	3%	10%	8%	2%	1%	1%
200	5%	3%	10%	8%	2%	< 0.1%	< 0.1%

← driven by δm_b via $\Gamma_{H\to b\bar{b}}$

EW corrections significant in predictions for $\Gamma_{H\to X}$ and $BR_{H\to X}$

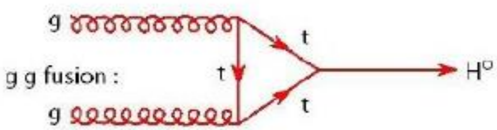
SM Higgs production and decays

For each coupling g_i, measure strength in "units" of SM value: $\kappa_i = g_i / g_{i,SM}$

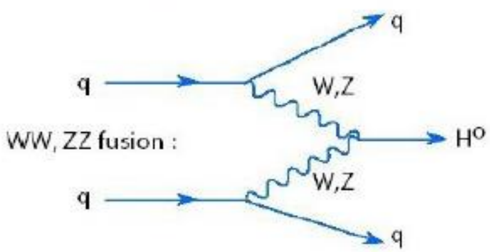
- Defined in analogy to signal strength $\mu = \sigma / \sigma_{SM}$

Production rate is proportional to squared coupling, g^2

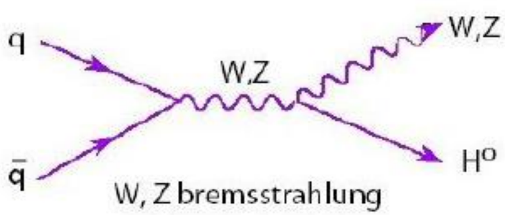
- Scaled each production mode *i* by factor κ_i^2



$\sim \kappa_g^2 \sim \kappa_t^2$ (loop coupling for gluons)

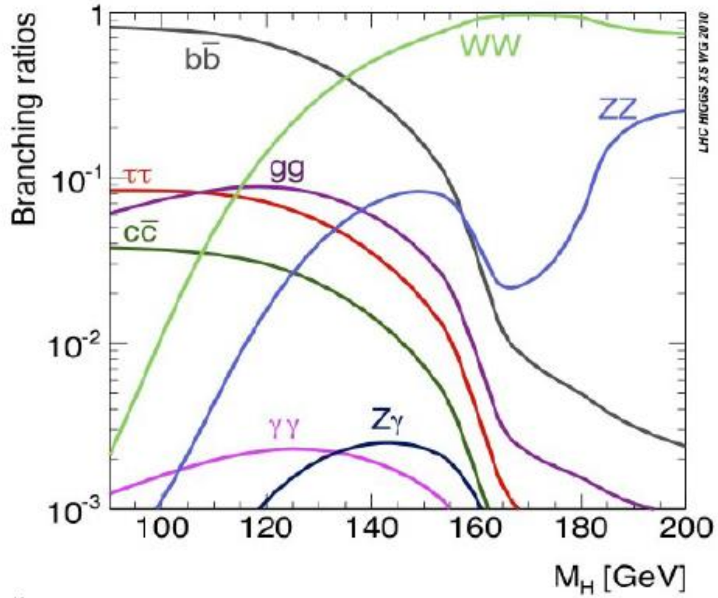


$\sim \kappa_{W,Z}^2$ (tree-level couplings)

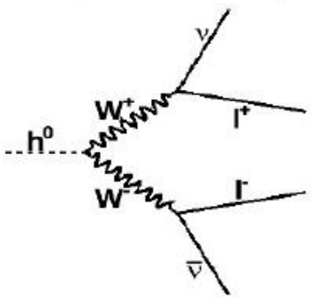


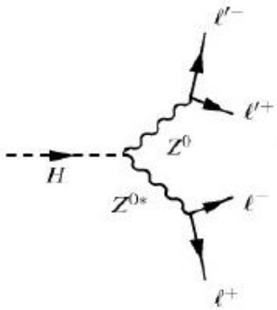
$\sim \kappa_{W,Z}^2$

SM Higgs production and decays



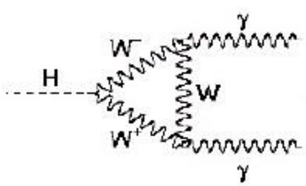
- Scaled each decay mode *j* by factor $\kappa_j^2 = g_j^2/g_{j,SM}^2$

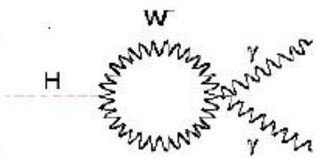


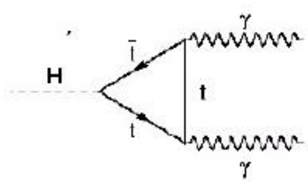


$\sim \kappa_{W,Z}^2$

(tree-level couplings)







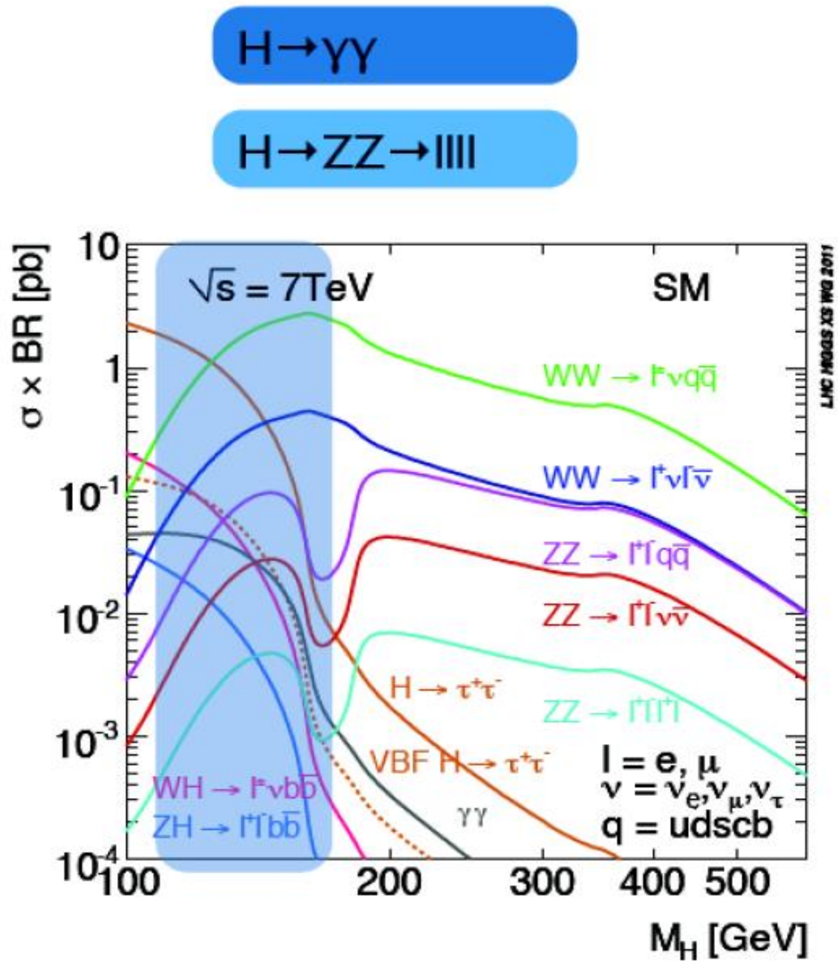
$\sim \kappa_\gamma^2 = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$

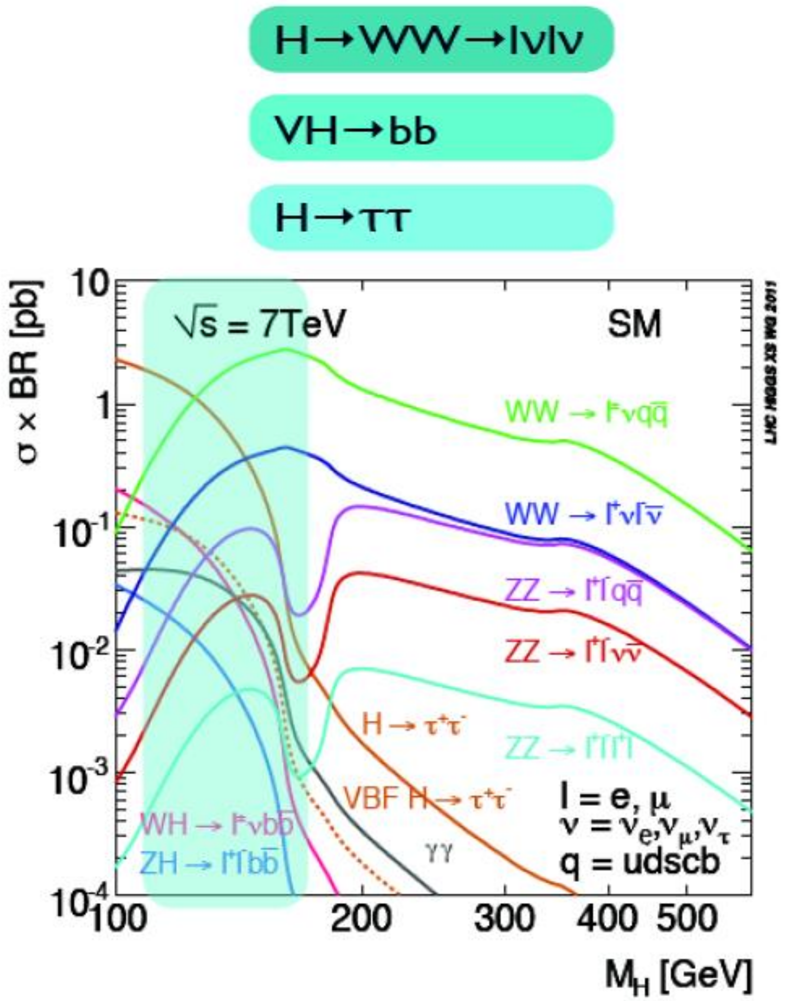
(loop coupling for photons)

- Example:

$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

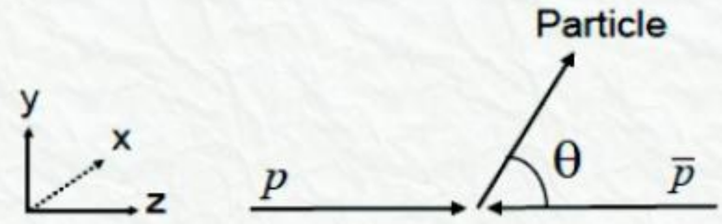
SM Higgs production at LHC





Some kinematic distributions

Rapidity (y) and Pseudo-rapidity (η)



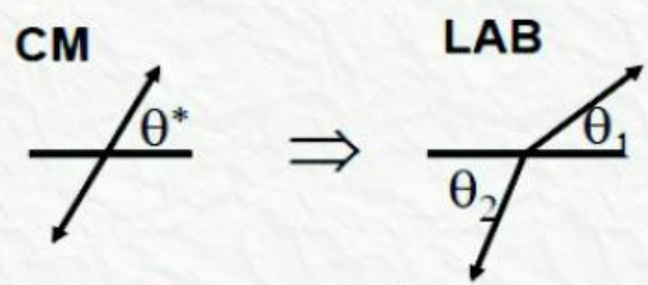
$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

$$\beta\cos\theta = \tanh y \quad \text{where } \beta = p/E$$

In the limit $\beta \to 1$ (or $m << p_T$) then

$$\eta \equiv y|_{m=0} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

LAB System ≠ parton-parton CM system



Δη and p_T are invariant under longitudinal boosts

Some kinematic definitions

Transverse Energy/Momentum

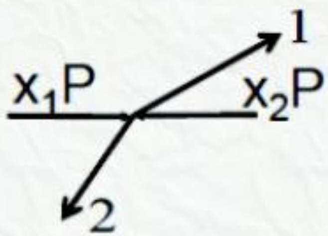
$$E_T^2 \equiv p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$$

$$p_z = E \tanh y$$
$$E = E_T \cosh y$$
$$p_z = E_T \sinh y$$

$$p_T \equiv p \sin\theta \xrightarrow[m \to 0]{} E_T$$

Invariant Mass

$$M_{12}^2 \equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$
$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)$$
$$\xrightarrow[m_1, m_2 \to 0]{} 2E_{T1}E_{T2}(\cosh\Delta\eta - \cos\Delta\phi)$$



Partonic Momentum Fractions

$$x_1 = \left(e^{\eta_1} + e^{\eta_2}\right)E_T / \sqrt{s}$$
$$x_2 = \left(e^{-\eta_1} + e^{-\eta_2}\right)E_T / \sqrt{s}$$

$$\text{Parton CM (energy)}^2 \rightarrow \hat{s} = x_a x_b s$$

$$x_T \equiv 2E_T / \sqrt{s} = x_{1,2}(\eta_{1,2} = 0)$$

$$0 < x_1, x_2 < 1$$
$$x_T^2 < x_1 x_2 < 1$$