Collider Physics

Lisboa 2012

1. Basic facts
2. Standard Model examples

Disclaimer

- The goal is to treat some of the basic elements aiming to make it easier to go to the literature
- Many details will not be mentioned
- Basic reference: Tao Han hep-ph/0508097
- Another reference: “QCD and Collider Physics” by Ellis, Stirling and Webber.

Motivation

- What we know:

$$\mathcal{L} = \mathcal{L}^{\rm f}_{\rm kinetic} + \mathcal{L}^{\rm GB}_{\rm kinetic} + \mathcal{L}_{\rm ffv} + \mathcal{L}_{\rm vvv} + \mathcal{L}_{\rm vvvv} + \mathcal{L}_{\rm EWSB}$$

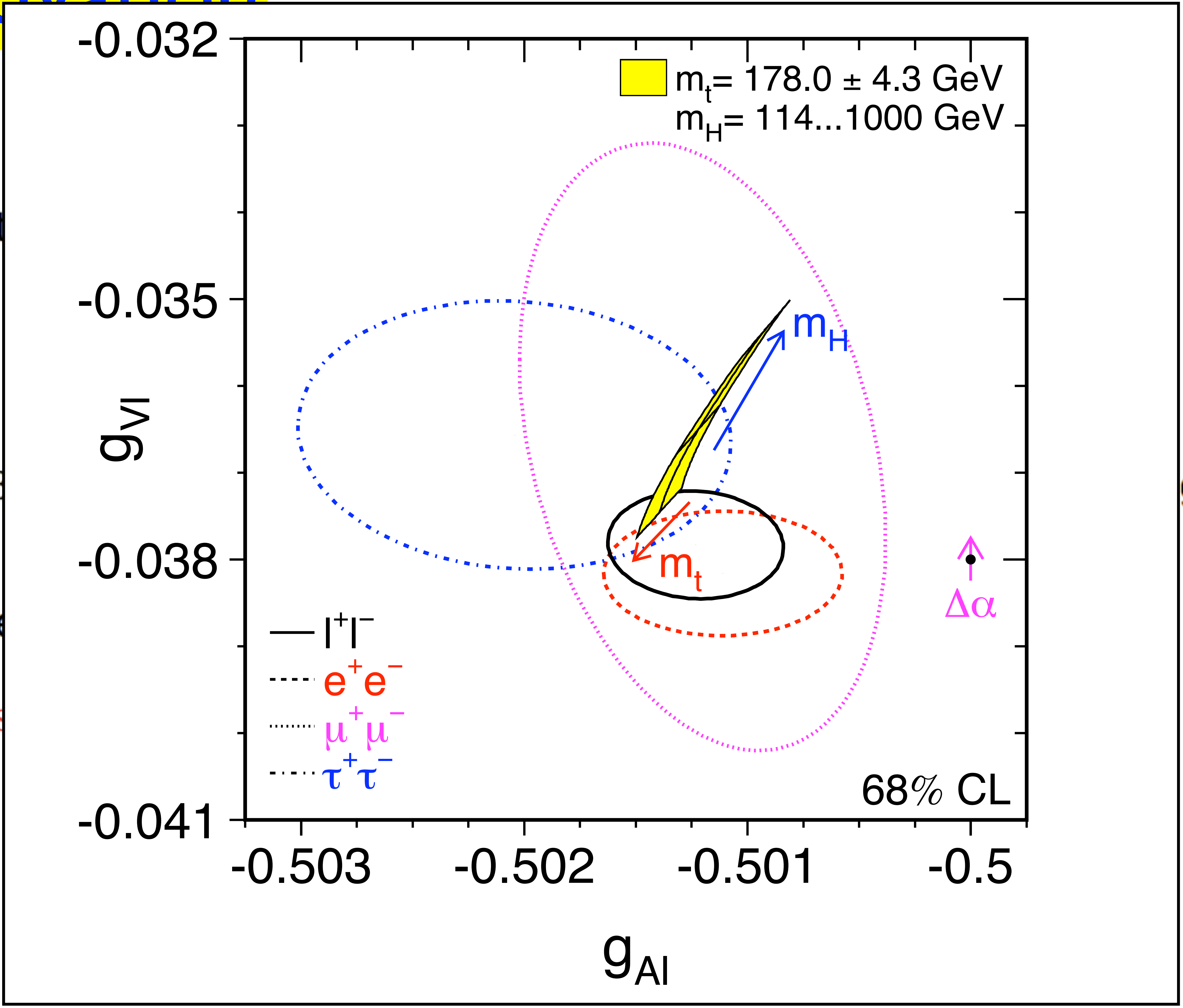
- $\mathbf{SU(3)_c \times SU(2)_L \times U(1)_Y}$ gauge interaction between fermions and gauge bosons tested at 0.1% level.

- Some information on the interactions between the gauge bosons

- $\mathcal{L}_{\rm EWSB}$ has not been directly tested: origin of masses, flavor physics, ...

Motivation

- What
- $\mathbf{SU}(3$ … gauge bosons
- Some
- $\mathcal{L}_{\mathrm{EWS}}$ … …



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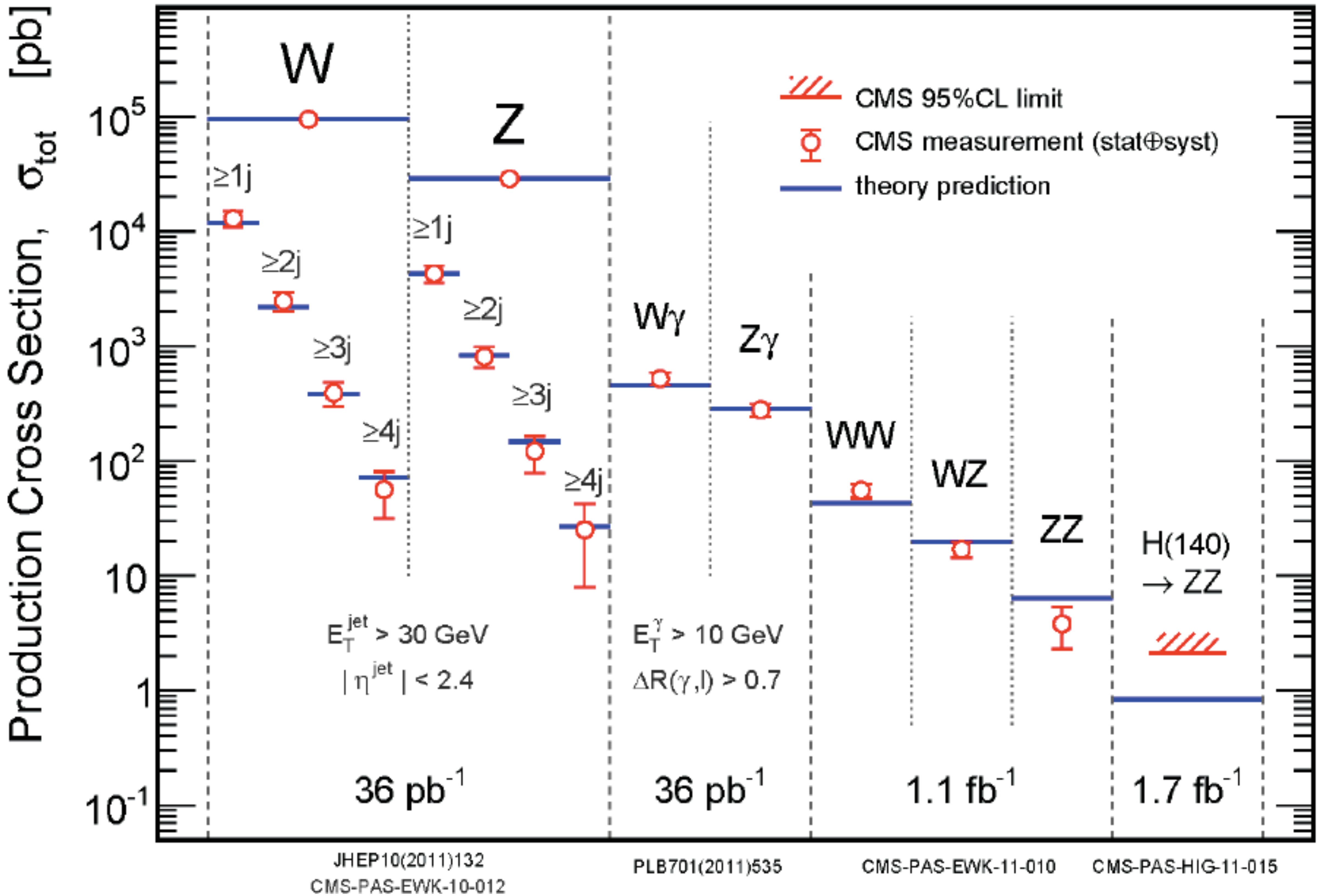
LHC has already enough data to start testing the SM and going beyond it



1. Basic Facts

- Collider parameters
- e^+e^- colliders
- Hadron colliders
- Detectors
- Useful kinematical variables
- Evaluation of scattering amplitudes

I. Collider parameters

- Relativity together with quantum mechanics lead to

$$\Delta p \, \Delta t > \frac{\hbar}{c}$$ ⇒ only asymptotic states are observable

⇓

colliders are essential

- Basic parameters

1. Center-of-mass energy $\mathbf{1+2 \longrightarrow X}$

$$\mathbf{s \equiv E_{CM}^2 \equiv (p_1+p_2)^2} = \begin{cases} (E_1+E_2)^2 & \text{in the c.m. frame } \vec{p}_1+\vec{p}_2=0, \\ m_1^2+m_2^2+2(E_1E_2-\vec{p}_1\cdot\vec{p}_2). \end{cases}$$

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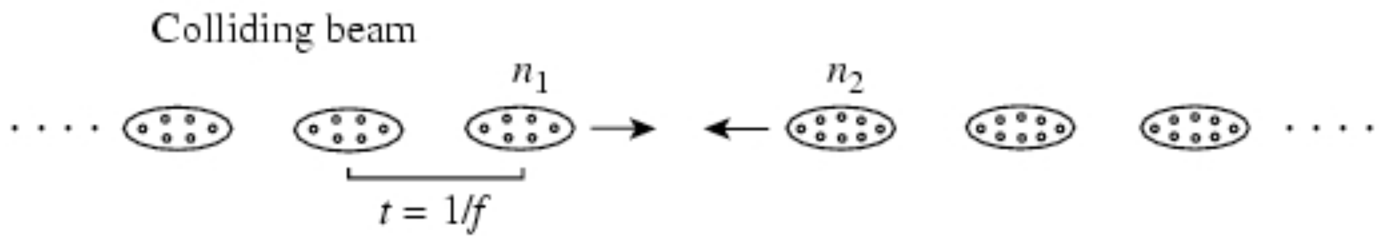
2. Instantaneous luminosity $\mathcal{L}$: event rate is proportional to σ

$$\mathbf{N}_{\text{events}} = \mathcal{L}\,\sigma(\mathbf{s})$$

machine ($\mathcal{L}$) physics ($\sigma(\mathbf{s})$)

• beams are a collection of bunches



$$\mathcal{L} \propto \frac{\mathbf{n_1 n_2 f}}{\mathbf{a}}$$

number of particles ($\mathbf{n_1}$, $\mathbf{n_2}$)

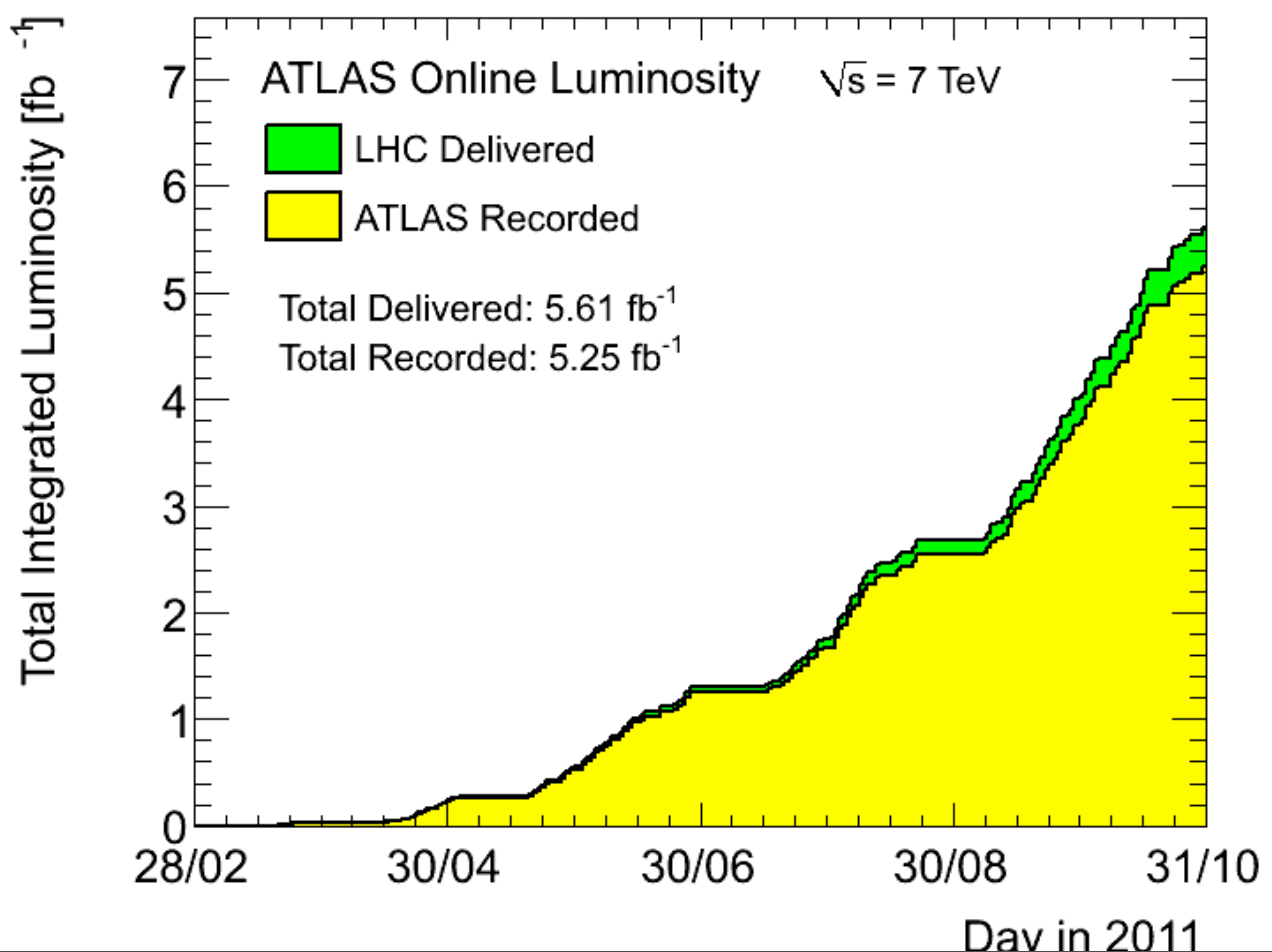
frequency ($\mathbf{f}$)

transverse area ($\mathbf{a}$)

- Important rule of a thumb: $\sigma \propto \mathbf{1/E_{CM}^2} \Longrightarrow \mathcal{L}$ grows as $\simeq \mathbf{E_{CM}^2}$

- Useful luminosity change of units

$$\mathbf{10^{33}}\ \mathrm{cm}^{\mathbf{-2}}\ \mathrm{s}^{\mathbf{-1}} = \mathbf{1}\ \mathrm{nb}^{\mathbf{-1}}\ \mathrm{s}^{\mathbf{-1}} \approx \mathbf{10}\ \mathrm{fb}^{\mathbf{-1}}/\mathrm{year}$$



II. e^+e^- colliders

- Main advantages:

  > e^+e^- interactions are well understood
  > Initial charges are zero => to produce new states
  > Scattering kinematics is well understood/constrained
  > In the CM frame all energy available to produce new states
  > It is possible to polarize the initial beams.

- Main disadvantages:

  > large synchroton radiation => linear machines
  > It is easier to produce spin-1 states in the s-channel
  > There are energy losses by bremstrahlung/beamsstrahlung
  > The energy spread needs to be taken into account

$$\int \mathbf{d}\tau \frac{\mathbf{d}\mathcal{L}}{\mathbf{d}\tau}\ \sigma(\hat{\mathrm{s}})\ \text{with}\ \tau = \sqrt{\hat{\mathrm{s}}}/\sqrt{\mathrm{s}}$$

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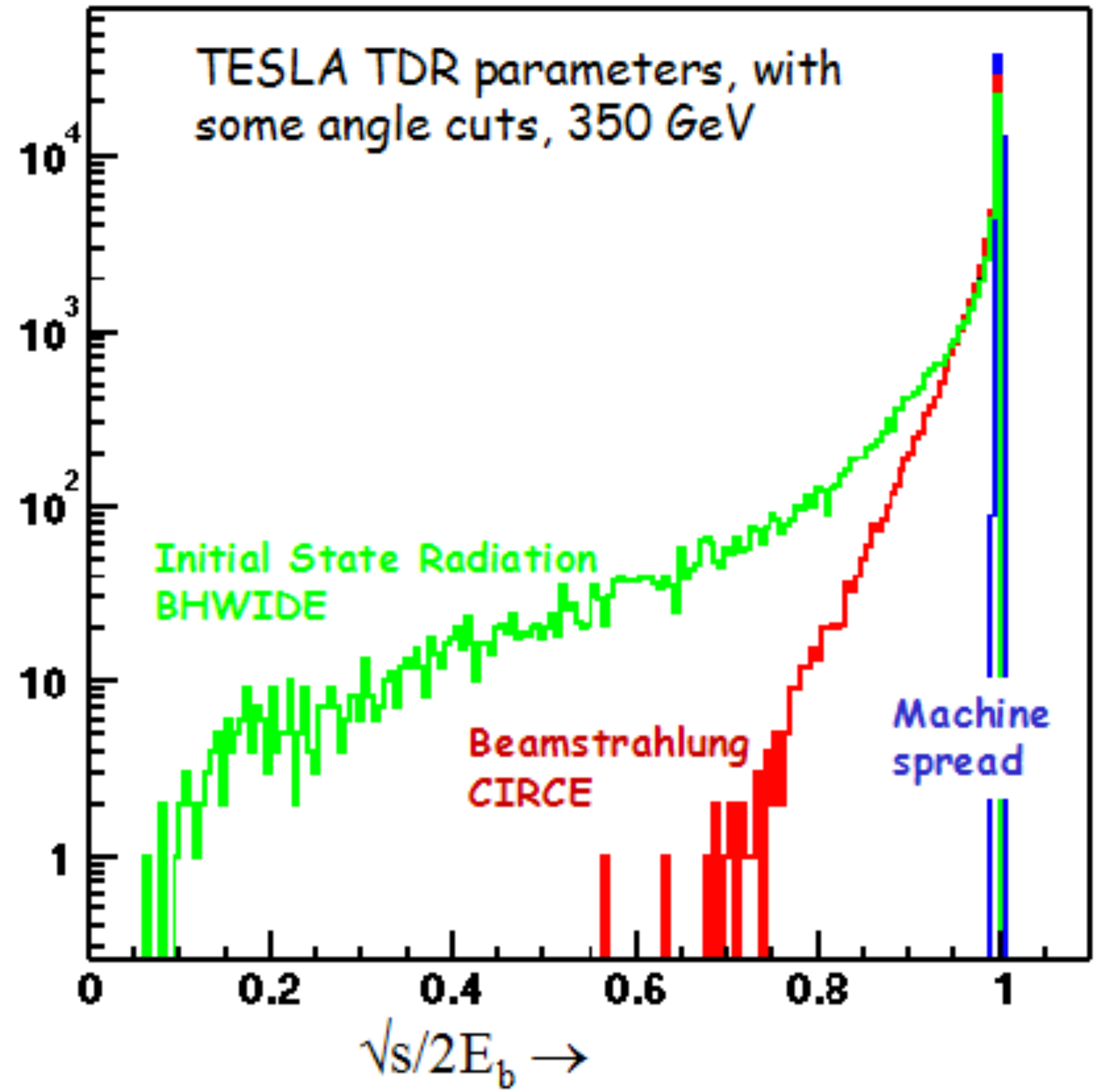

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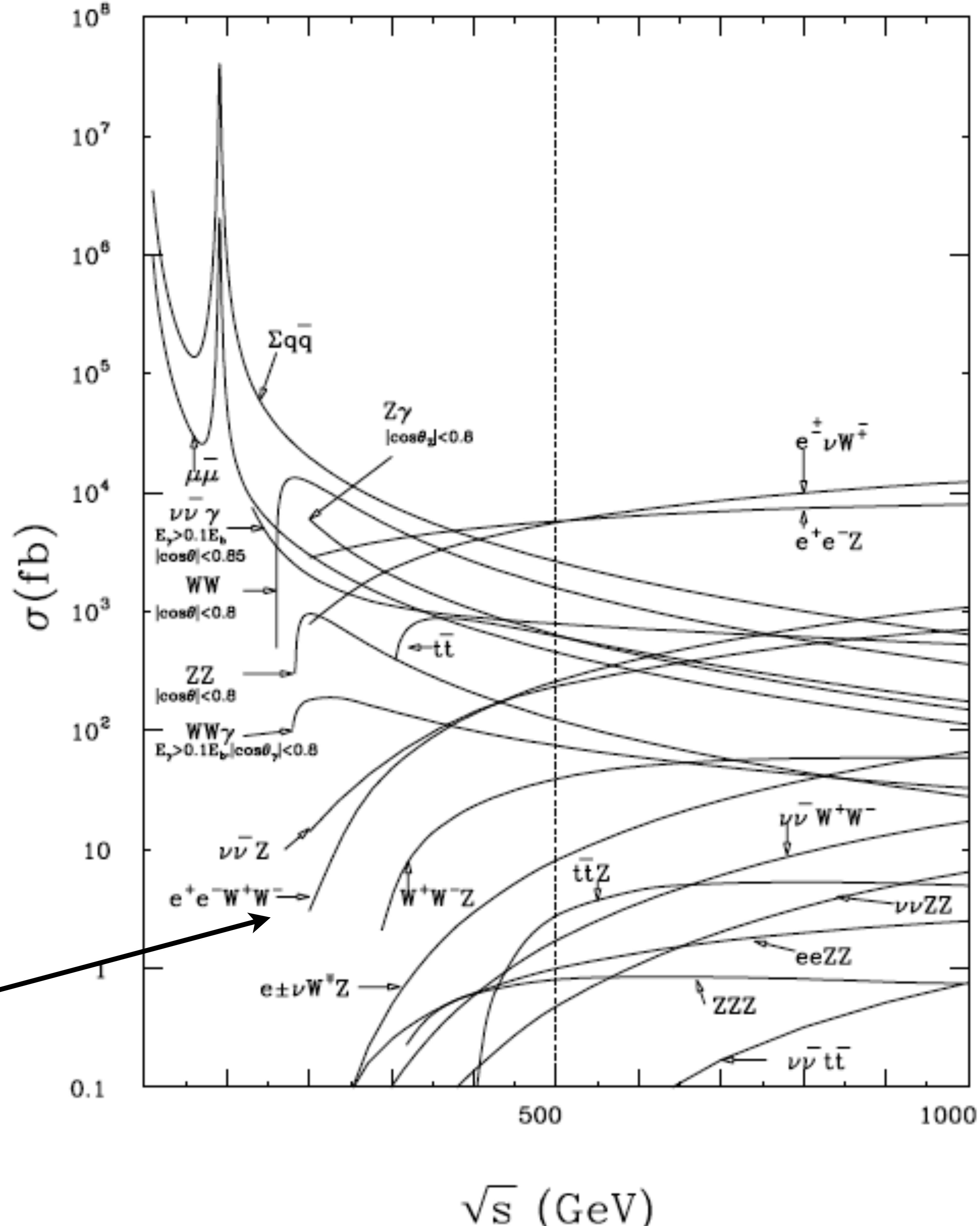
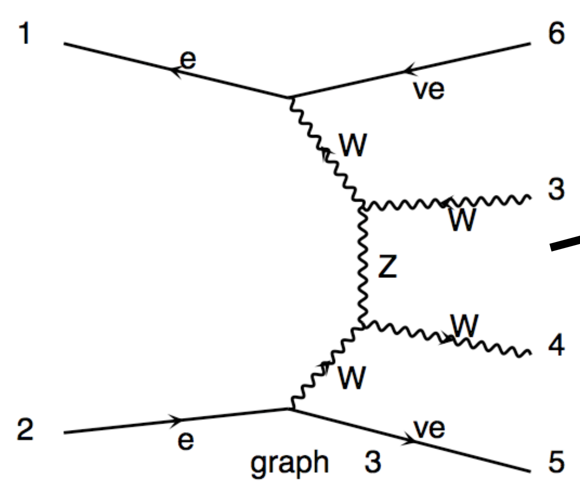
- SM processes

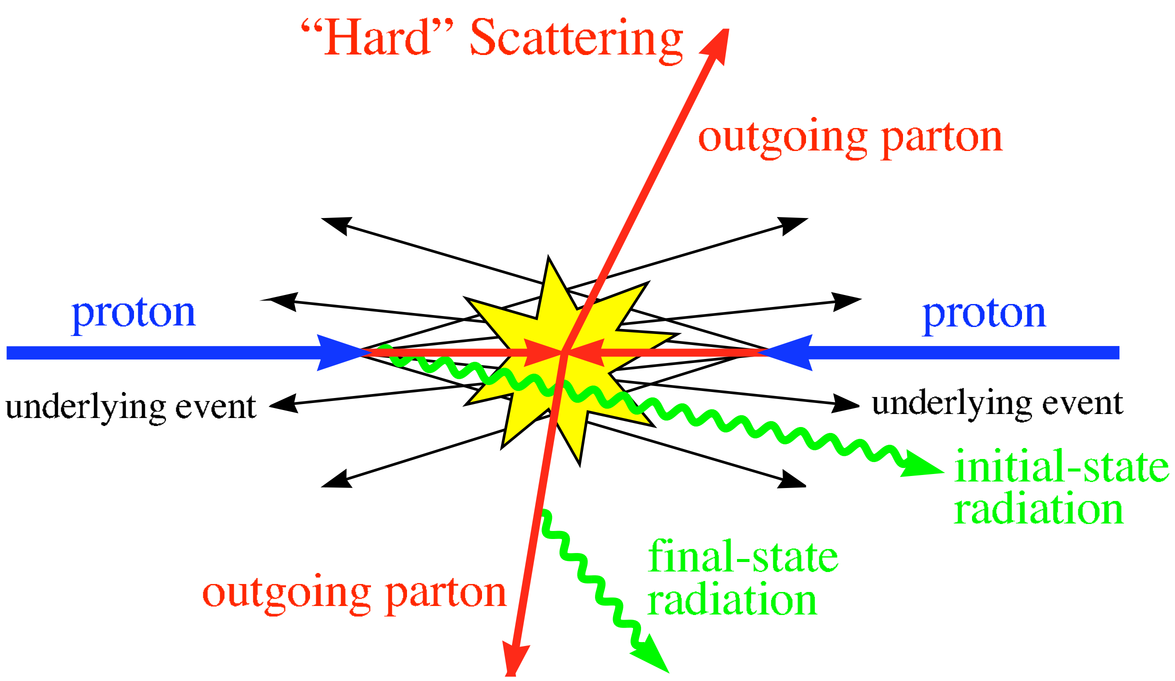
σ (fb)





III. Hadron colliders

- protons are much heavier than electrons => higher CM energies
- higher luminosities can be achieved
- protons are composed of quarks and gluons => fewer kinematical constraints
- protons are strongly interacting: collisions are messier
- strong interactions => large cross sections $\sigma_{\text{total}} \simeq \mathbf{100}\ \text{mb}$



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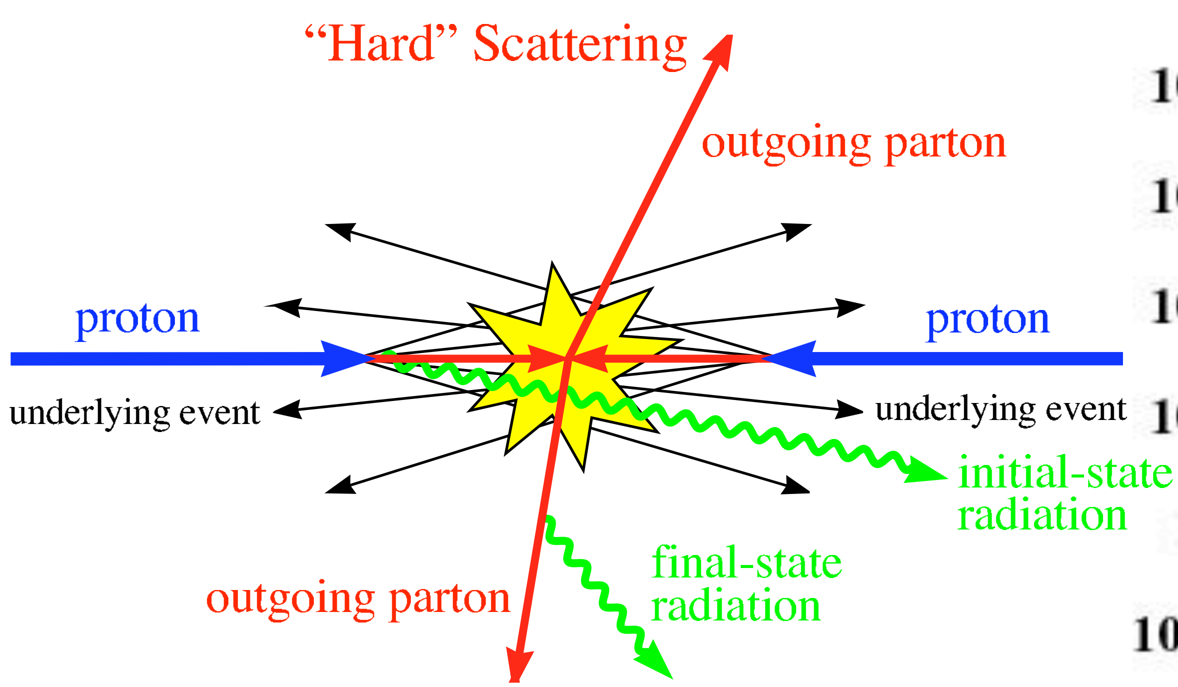
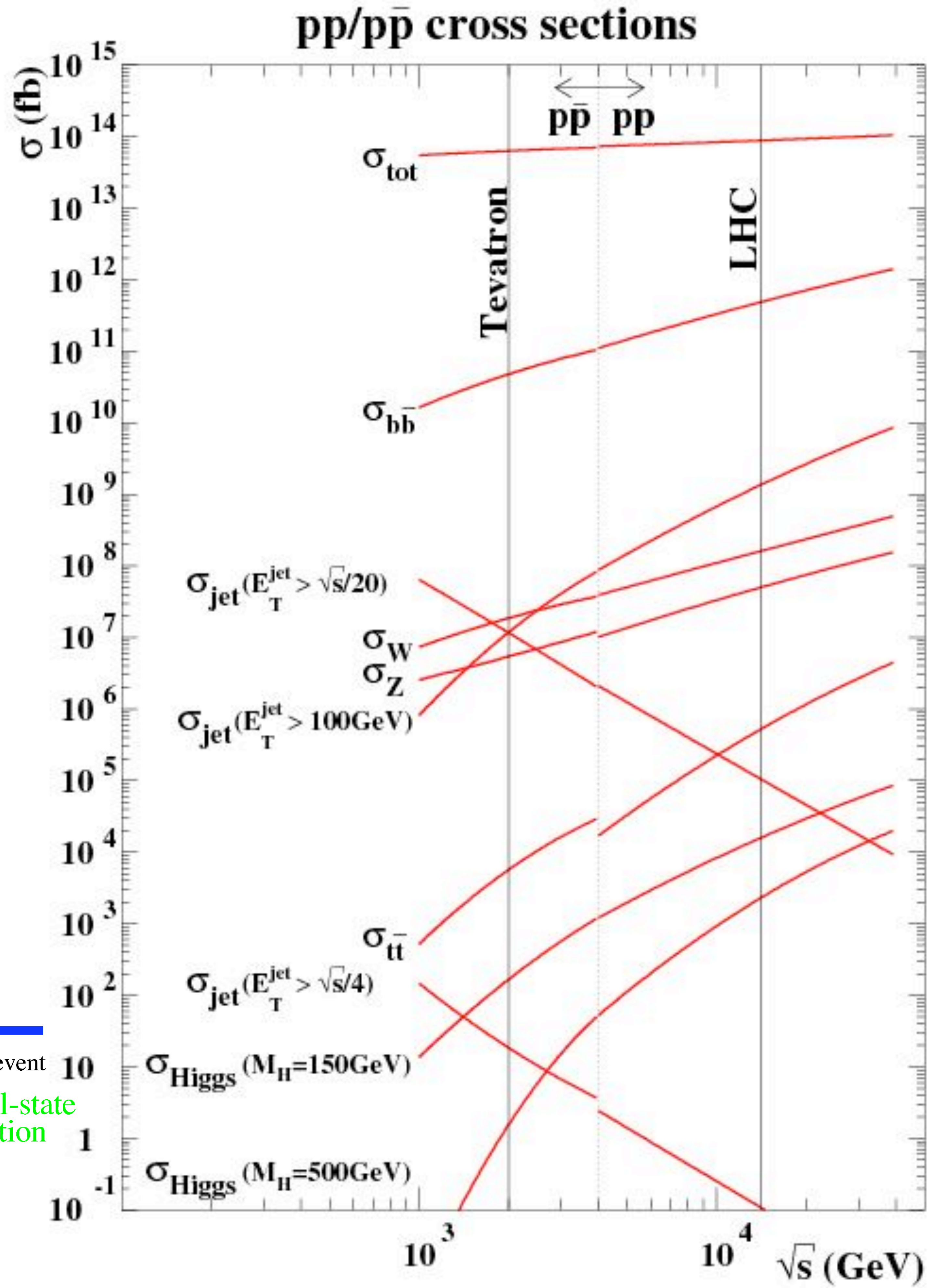




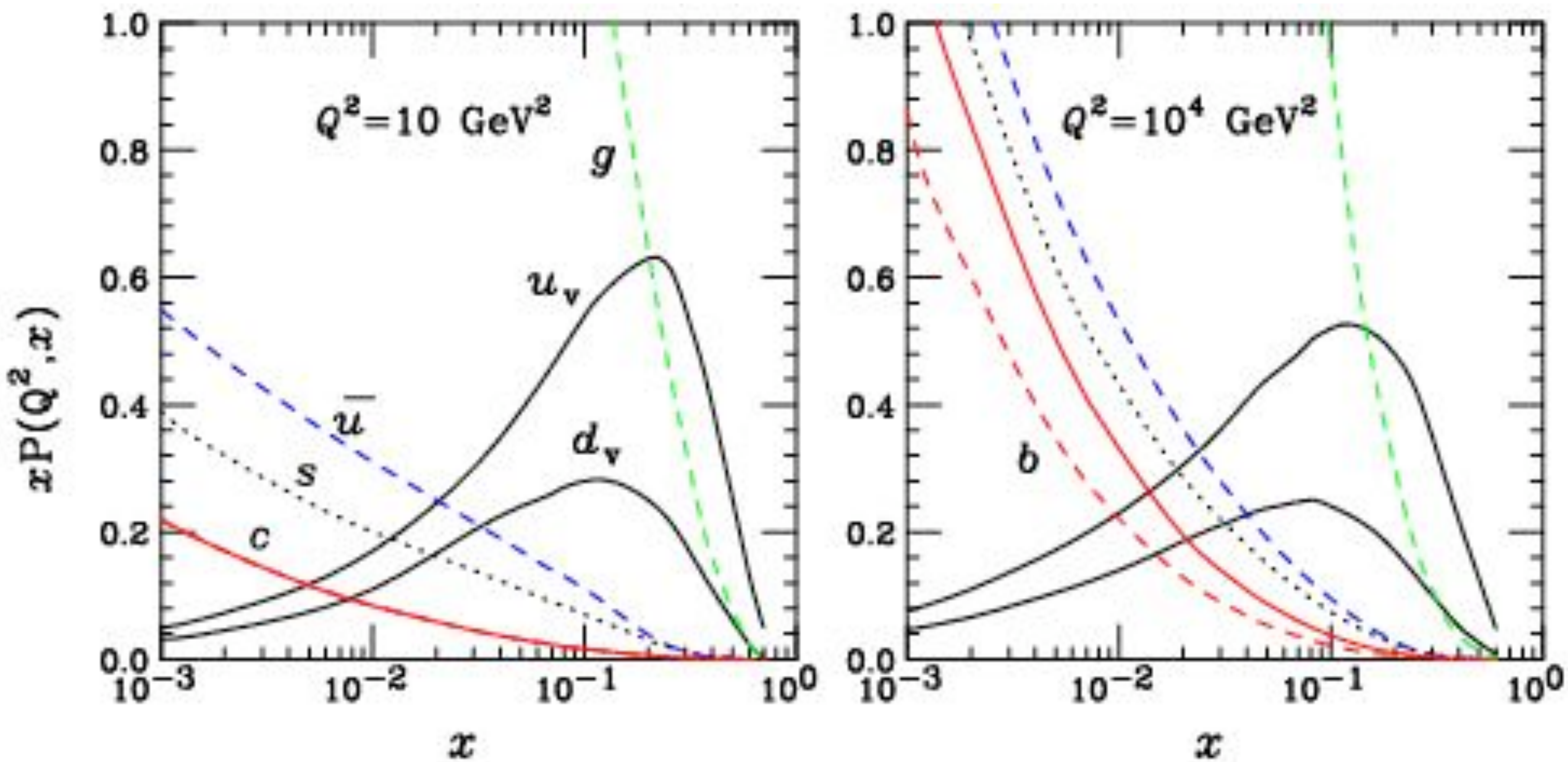
- QCD factorization theorem: for large transfer momentum we have

$$\sigma(\mathbf{AB} \to \mathbf{F}\ \mathbf{X}) = \sum_{\mathbf{a,b}} \int \mathbf{dx_1 dx_2}\ \mathbf{f_{a/A}(x_1, Q^2) f_{b/B}(x_2, Q^2)}\ \hat{\sigma}(\mathbf{ab} \to \mathbf{F})$$

inclusive   distribution functions   parton-parton scattering

- $\mathbf{f_{b/B}(x, Q^2)}$ is de b parton density in the hadron B carrying x of the momentum

characteristic scale



Useful quantity:

$$\sigma(s) = \sum_{a,b} \int dx_1 dx_2 \; f_{a/A}(x_1) f_{b/B}(x_2) \; \hat{\sigma}(\hat{s})$$

$$= \sum_{a,b} \int d\tau \int \frac{dx}{x} f_{a/A}(x) f_{b/B}(\tau/x) \; \hat{\sigma}(\tau s)$$

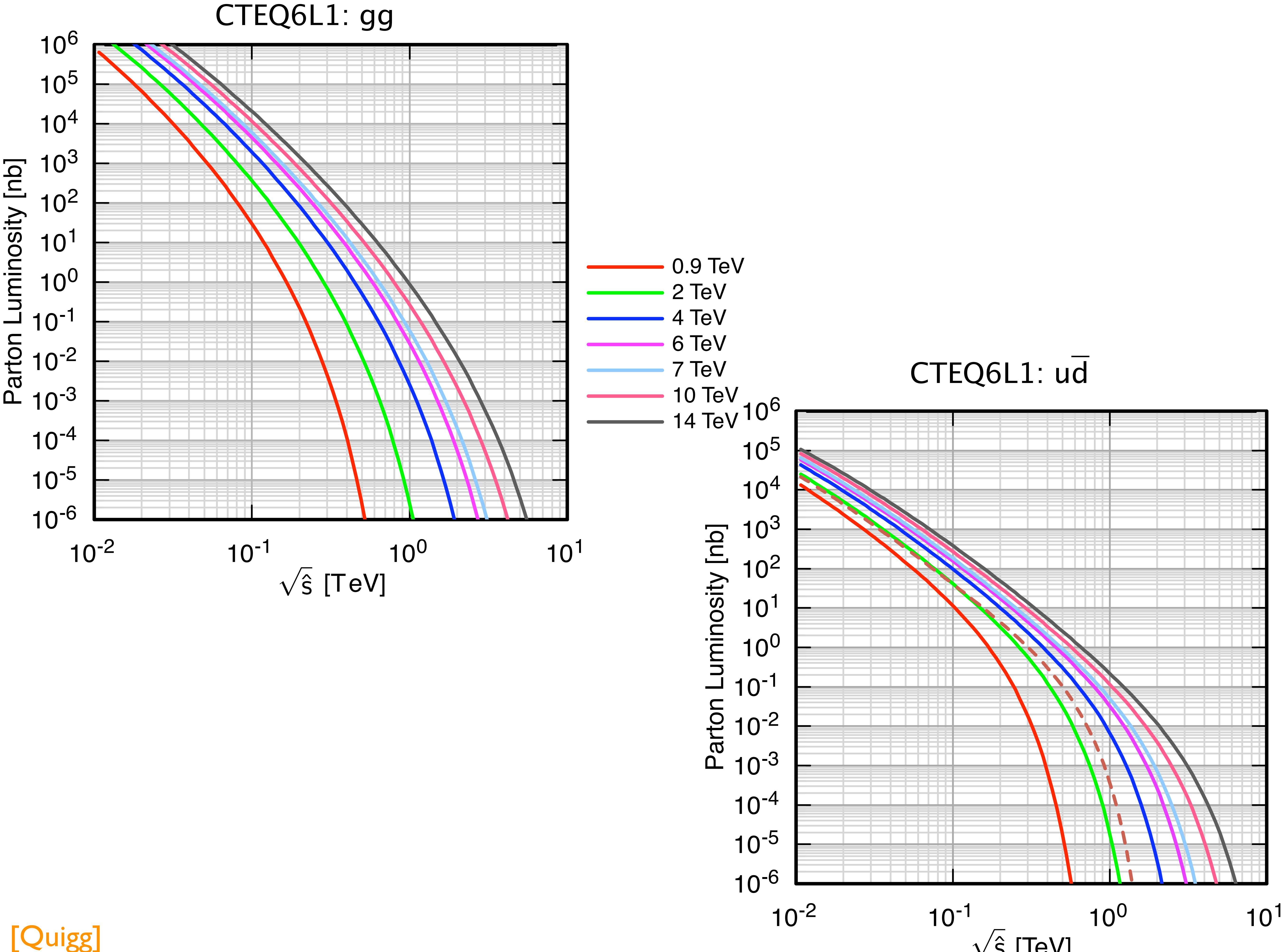
where $\tau = \mathbf{x_1 x_2}$

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

dimensionless

we define the parton-parton luminosity

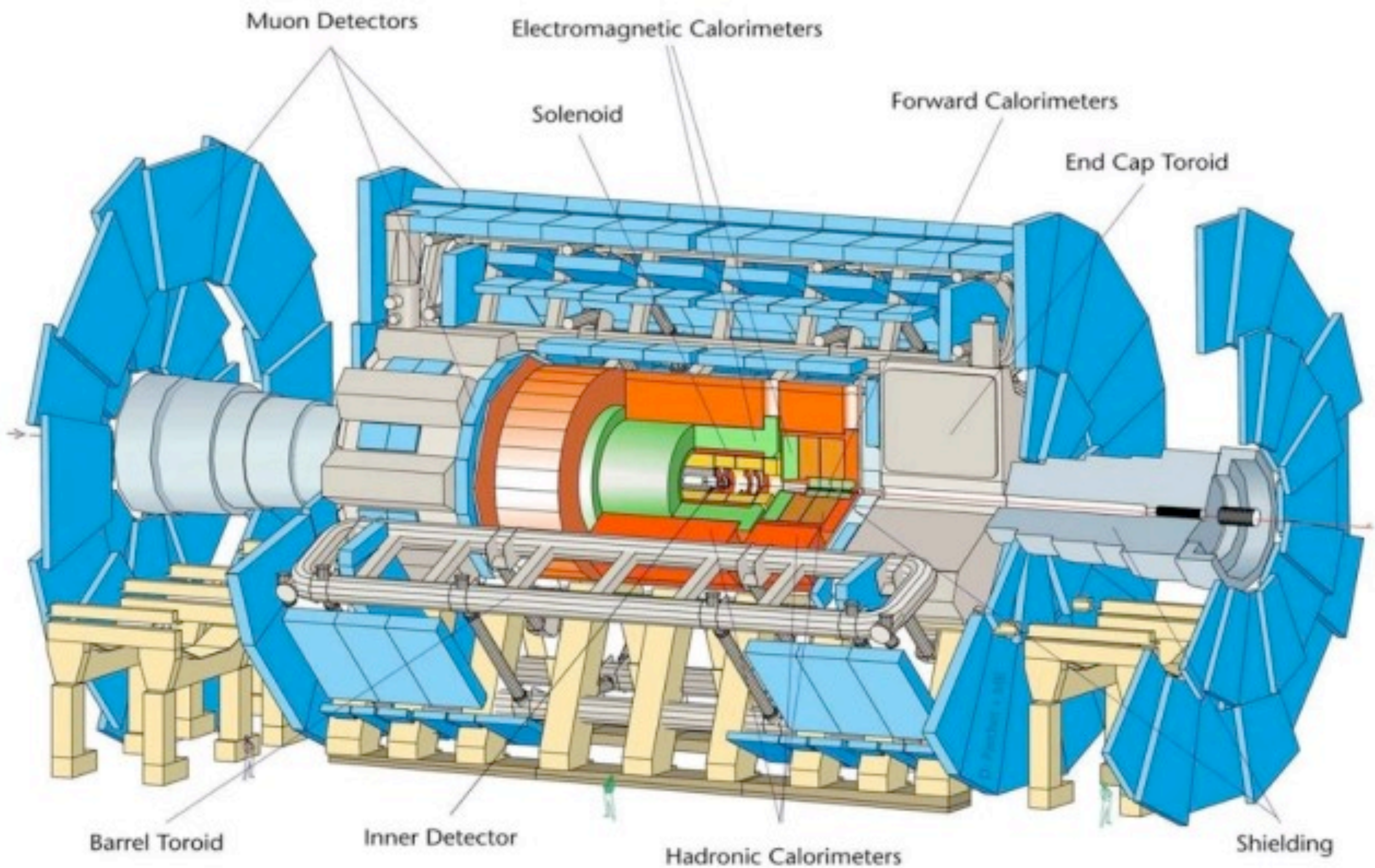
$$\frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \equiv \frac{\tau/\hat{s}}{1+\delta_{ij}} \int_{\tau}^{1} dx [f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x)]/x$$


CTEQ6L1: gg
Parton Luminosity [nb]
$\sqrt{\hat{s}}$ [TeV]
0.9 TeV
2 TeV
4 TeV
6 TeV
7 TeV
10 TeV
14 TeV
CTEQ6L1: $u\bar{d}$
Parton Luminosity [nb]
$\sqrt{\hat{s}}$ [TeV]

[Quigg]

IV. Detectors

- Goal: measure position, time, momentum, energy, type,....
- modern detectors are very complex.



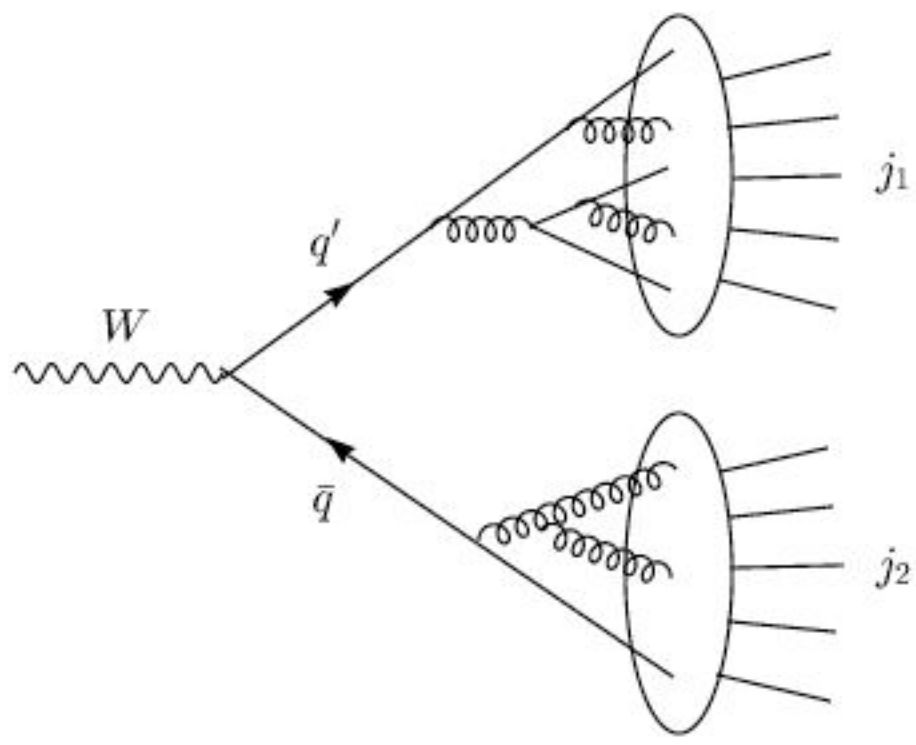
- The signal of a particle depends on its interactions and decay length

$$\mathbf{d} = (\beta\ \mathbf{c}\tau)\frac{\mathbf{E}}{\mathbf{M}} \approx (\mathbf{300}\ \mu\mathbf{m})\left(\frac{\tau}{\mathbf{10^{-12}\ s}}\right)\ \frac{\mathbf{E}}{\mathbf{M}}$$

- There are a few possibilities:
    - Fast decay, eg, gluons hadronize in

$$\mathbf{t_h} \sim \mathbf{1}/\mathbf{\Lambda_{QCD}} \approx \mathbf{1}/(\mathbf{200}\ \ \mathrm{MeV}) \approx \mathbf{3.3} \times \mathbf{10}^{-\mathbf{24}}\ \ \mathbf{s}$$

energetic q/g produce jets



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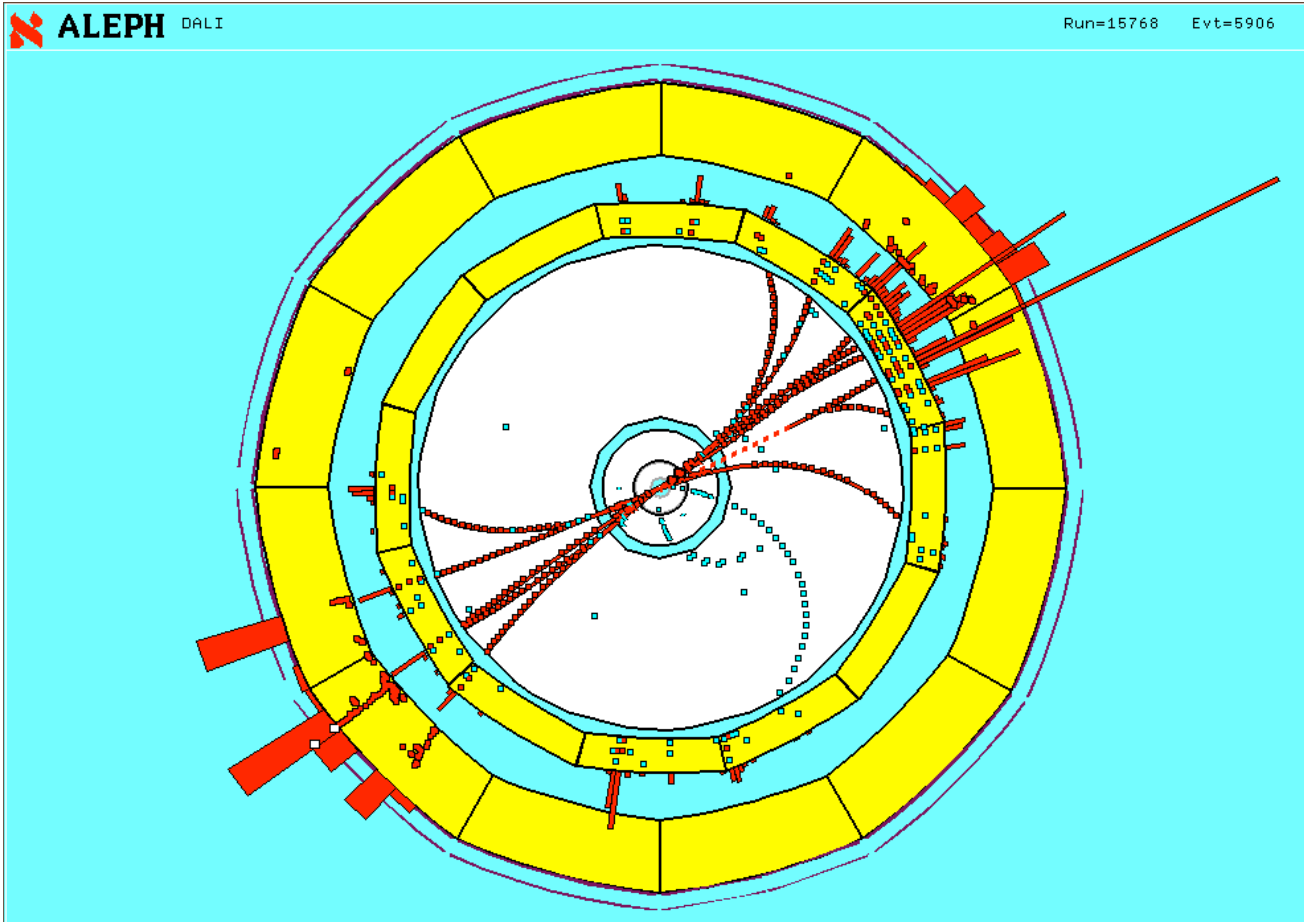

- stable particles: $(\mathbf{p},\ \bar{\mathbf{p}},\ \mathbf{e}^{\pm},\ \gamma)$ leave energy deposit and/or tracks

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- Quasi-stable particles: behave like the stable ones

$$(\tau > \mathbf{10^{-10}}\ \mathrm{s,\ e.g.}\quad \mathbf{n}, \mathbf{\Lambda}, \mathbf{K^0_L},\ ...\ \mu^{\pm},\ \pi^{\pm}, \mathbf{K}^{\pm},\ ...)$$

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- Short lived resonances decay promptly $\mathbf{W}^{\pm},\ \mathbf{Z}(\mathbf{10^{-25}}\ \mathrm{s}); \pi^{\mathbf{0}}, \rho, \ldots$

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- Displaced vertices:

$B^{0,\pm},\ D^{0,\pm},\ \tau^{\pm}, (\tau \sim 10^{-12}\ \mathrm{s};\ c\tau \sim 100\ \mu\mathrm{m}).\ K^0_S \to \pi^+\pi^-\ \mathrm{w/}\ c\tau \sim 2.7\ \mathrm{cm}$

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- Neutral weakly interacting particles leave no signal (ν)

- More complex analyses can be made

Leptons	Vertexing	Tracking	ECAL	HCAL	Muon Cham.
$e^\pm$	$\times$	$\vec{p}$	E	$\times$	$\times$
$\mu^\pm$	$\times$	$\vec{p}$	$\surd$	$\surd$	$\vec{p}$
$\tau^\pm$	$\surd\times$	$\surd$	$e^\pm$	$h^\pm;\ 3h^\pm$	$\mu^\pm$
ν_e, ν_μ, ν_τ	$\times$	$\times$	$\times$	$\times$	$\times$
Quarks					
u, d, s	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$c \longrightarrow D$	$\surd$	$\surd$	$e^\pm$	h's	$\mu^\pm$
$b \longrightarrow B$	$\surd$	$\surd$	$e^\pm$	h's	$\mu^\pm$
$t \longrightarrow bW^\pm$	b	$\surd$	$e^\pm$	$b + 2$ jets	$\mu^\pm$
Gauge bosons					
γ	$\times$	$\times$	E	$\times$	$\times$
g	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$W^\pm \longrightarrow \ell^\pm \nu$	$\times$	$\vec{p}$	$e^\pm$	$\times$	$\mu^\pm$
$\longrightarrow q\bar{q}'$	$\times$	$\surd$	$\surd$	2 jets	$\times$
$Z^0 \longrightarrow \ell^+\ell^-$	$\times$	$\vec{p}$	$e^\pm$	$\times$	$\mu^\pm$
$\longrightarrow q\bar{q}$	$(b\bar{b})$	$\surd$	$\surd$	2 jets	$\times$

- Typical detector performance:
  - > Coverage: $|\eta_{\mathbf{track}}| < \mathbf{2.5} \quad |\eta_{\mathbf{cal}}| < \mathbf{5.}$
  - > Tracker momentum resolution

$$\frac{\mathbf{\Delta p_T}}{\mathbf{p_T}} = \mathbf{0.36 p_T} \oplus \frac{\mathbf{0.013}}{\sqrt{\sin\theta}} \text{ (in TeV)}$$

  - > ECAL resolution:

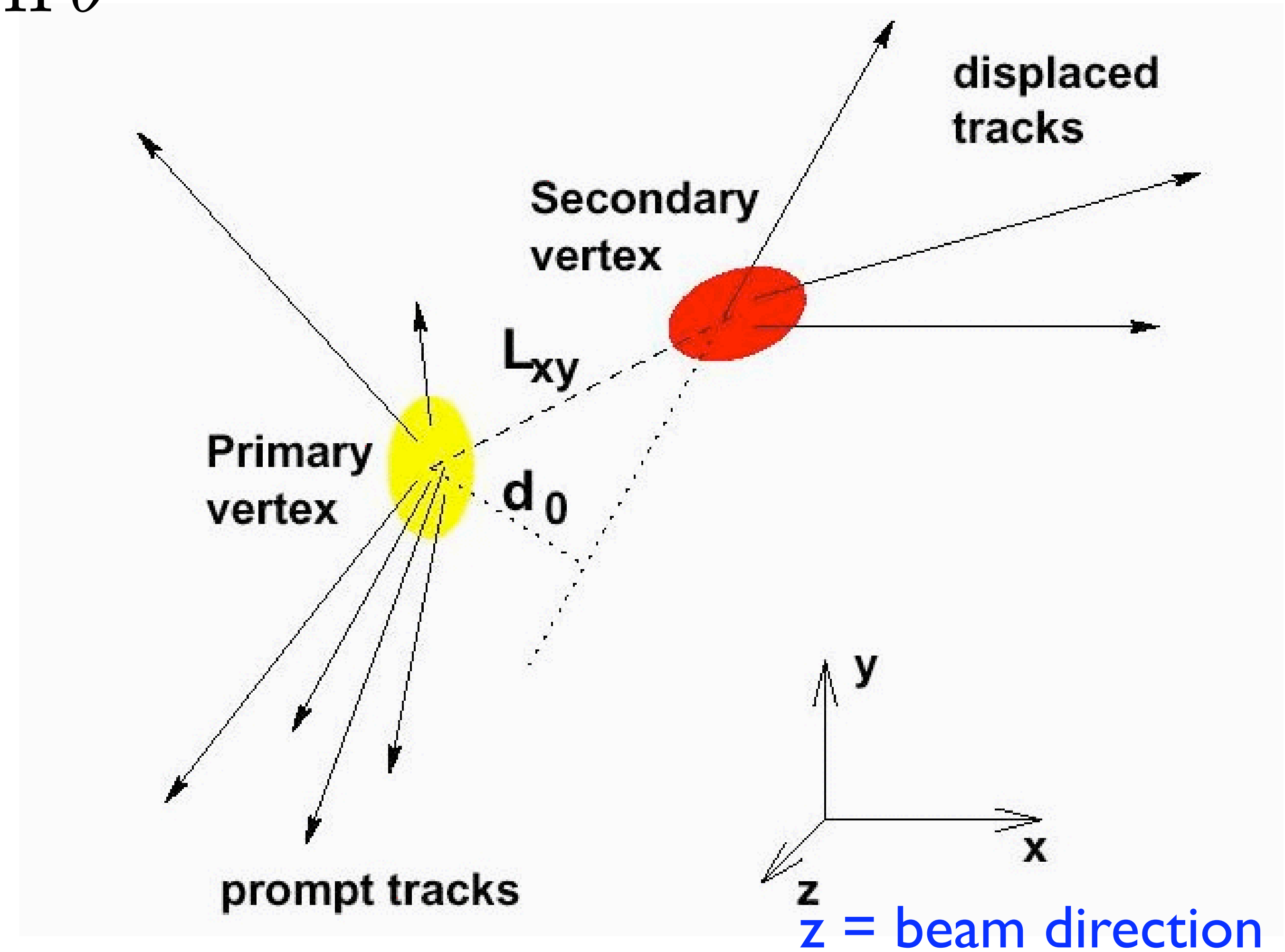
$$\frac{\mathbf{\Delta E}}{\mathbf{E}} = \frac{\mathbf{10\%}}{\sqrt{\mathbf{E}/\mathrm{GeV}}} \oplus \mathbf{0.4\%}$$

  - > HCAL resolution

$$\frac{\mathbf{\Delta E}}{\mathbf{E}} = \frac{\mathbf{80\%}}{\sqrt{\mathbf{E}/\mathrm{GeV}}} \oplus \mathbf{15\%}$$

> Vertexing performance:

$$\Delta \mathbf{d_0} = \mathbf{11} \oplus \frac{\mathbf{73}}{(\mathbf{p_T}/\ \mathrm{GeV})\ \sqrt{\sin\theta}}\ (\mu\mathrm{m})$$



$$\Delta \mathbf{z_0} = \mathbf{87} \oplus \frac{\mathbf{115}}{(\mathbf{p_T}/\ \mathrm{GeV})\ \sqrt{\sin^{\mathbf{3}}\theta}}\ (\mu\mathrm{m})$$

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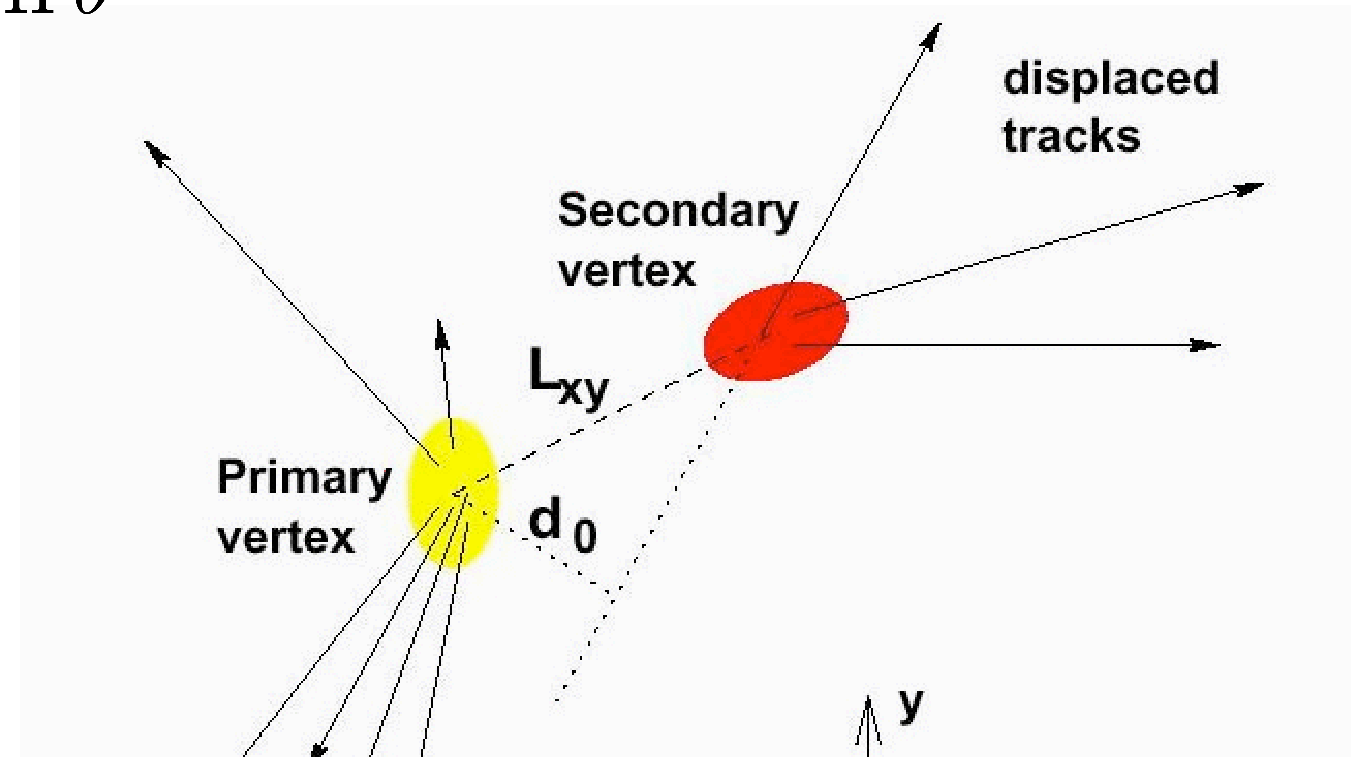
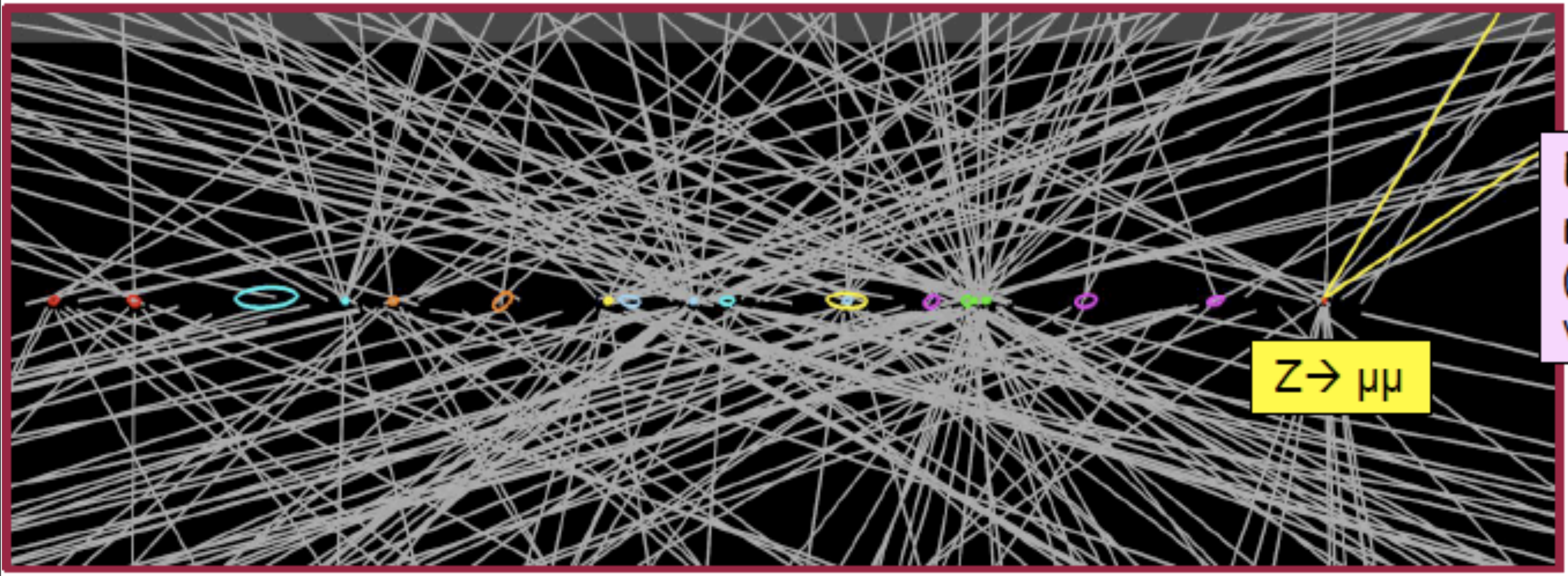




Event with 20 reconstructed vertices (ellipses have 20 σ size for visibility reasons)

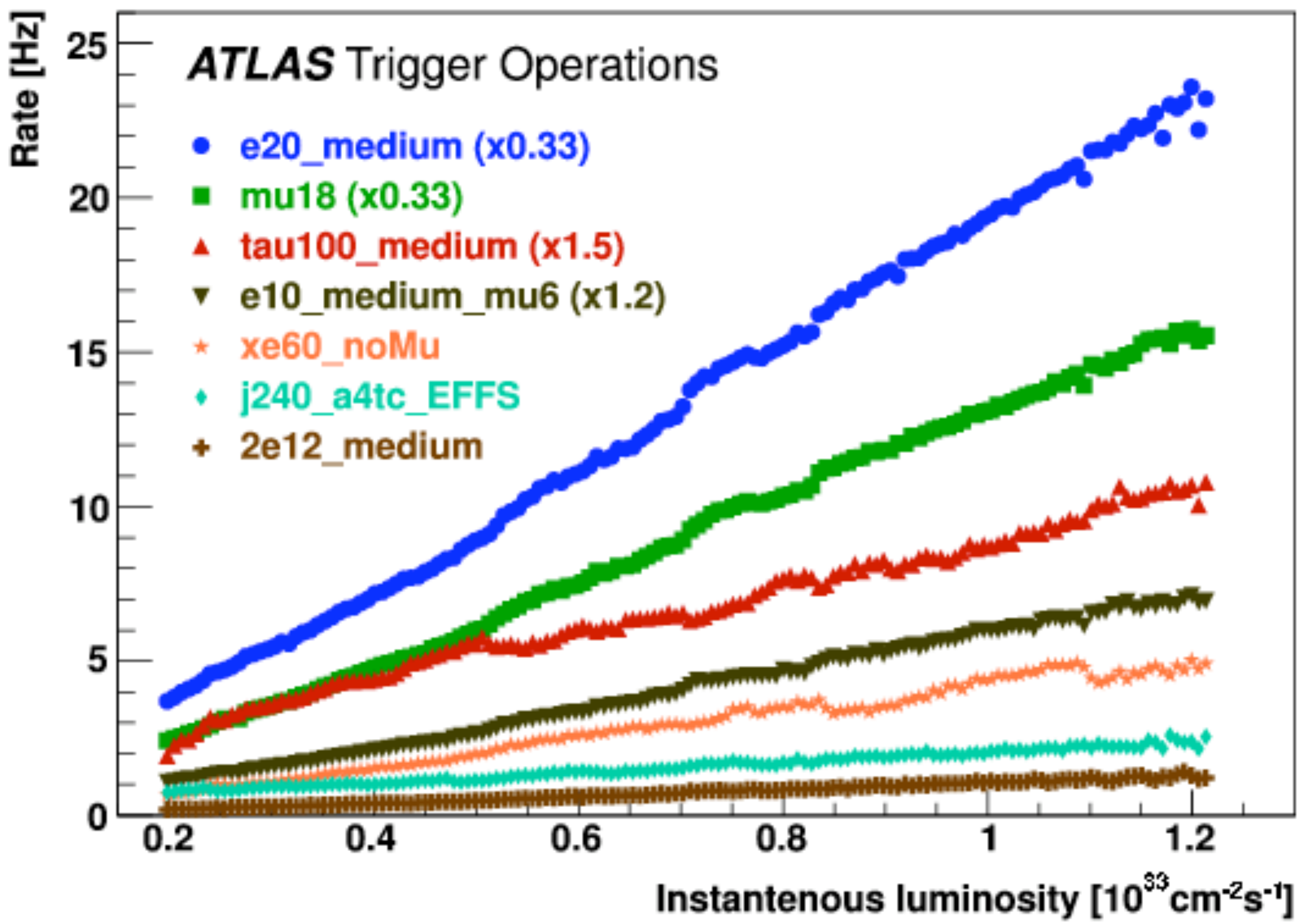
Gianotti

- Trigger: for large events rates, eg, at LHC it is 40 MHz, it is impossible to store all events.

- At the LHC a event rate of 200 Hz can be stored!!!

- the trigger is a fast selection to reduce the event rate for writing.

- There are several layers of decision (level-1, level-2, etc)



V. Useful kinematical variables

- Subprocess center-of-mass energy: in the LAB frame

$$\mathbf{p}^{\mu}_{\mathbf{CM}} =\simeq \frac{\sqrt{\mathbf{s}}}{\mathbf{2}}(\mathbf{x_1}+\mathbf{x_2},\mathbf{0},\mathbf{0},\mathbf{x_1}-\mathbf{x_2}) \quad \Longrightarrow \quad \hat{\mathbf{s}} = \mathbf{x_1}\mathbf{x_2}\mathbf{s}$$

- Rapidity/pseudo-rapidity: $\mathbf{E}(\mathbf{1},\beta\sin\theta\cos\phi,\beta\sin\theta\sin\phi,\beta\cos\theta)$

$$\mathbf{y} \equiv \frac{\mathbf{1}}{\mathbf{2}}\log\frac{\mathbf{E}+\mathbf{p_z}}{\mathbf{E}-\mathbf{p_z}} \longrightarrow \eta = \frac{\mathbf{1}}{\mathbf{2}}\log\frac{\mathbf{1}+\cos\theta}{\mathbf{1}-\cos\theta} \quad \text{for} \quad \beta\to\mathbf{1}$$

- The CM and LAB frames are related by

$$\mathbf{y} = \mathbf{y}^* + \mathbf{y}_{\mathbf{c.m.}} = \mathbf{y}^* + \frac{\mathbf{1}}{\mathbf{2}}\log\frac{\mathbf{x_1}}{\mathbf{x_2}}$$

center-of-mass rapidity

V. Use

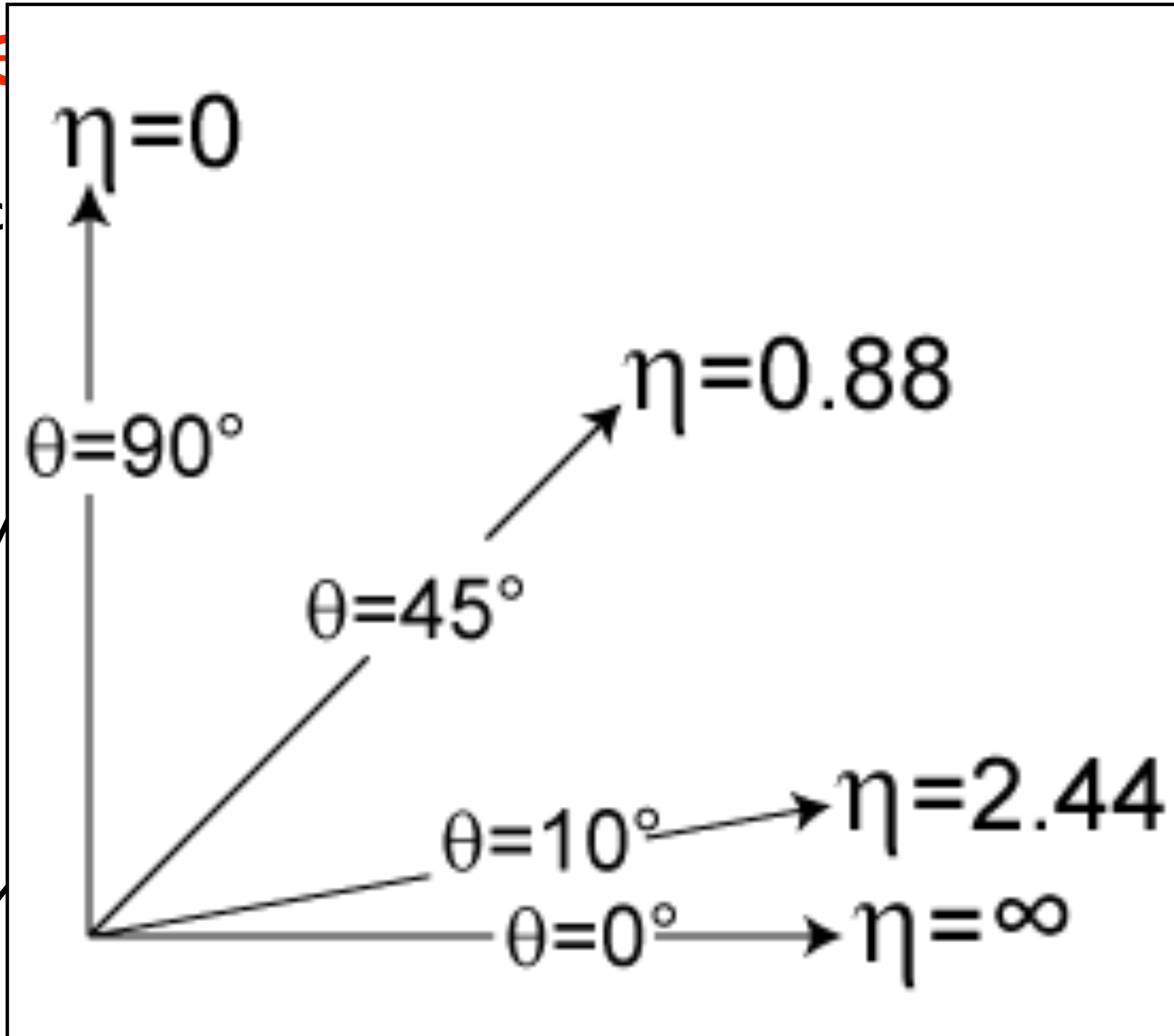
• Subproc

$\mathbf{p}^{\mu}_{\mathrm{CM}}$ ... $\mathbf{x_1 x_2 s}$

• Rapidity ... $\phi, \beta \cos\theta)$

$\mathbf{y} \equiv$ ... $\rightarrow \mathbf{1}$

• The CM



$\mathbf{2}$ ... $\mathbf{x_2}$

center-of-mass rapidity

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center-of-mass rapidity

- A useful change of variables is

$$\mathbf{x_{1,2}} = \sqrt{\tau}\ \mathbf{e}^{\pm \mathbf{y_{cm}}} \quad \Longrightarrow \quad \int_{\tau_0}^{1} \mathbf{dx_1} \int_{\tau_0/\mathbf{x_1}}^{1} \mathbf{dx_2} = \int_{\tau_0}^{1} \mathbf{d}\tau \int_{\frac{1}{2}\ln\tau}^{-\frac{1}{2}\ln\tau} \mathbf{dy_{cm}}$$

- Largely used due to $\dfrac{\mathbf{d^3\tilde{p}}}{\mathbf{E}} = \mathbf{dpxdpy}\dfrac{\mathbf{dp_z}}{\mathbf{E}} = \mathbf{p_T dp_T d}\varphi\mathbf{dy}$

with the φ (azimuthal angle), $\mathrm{p_T}$ (transverse momentum) and y being invariant under longitudinal boosts

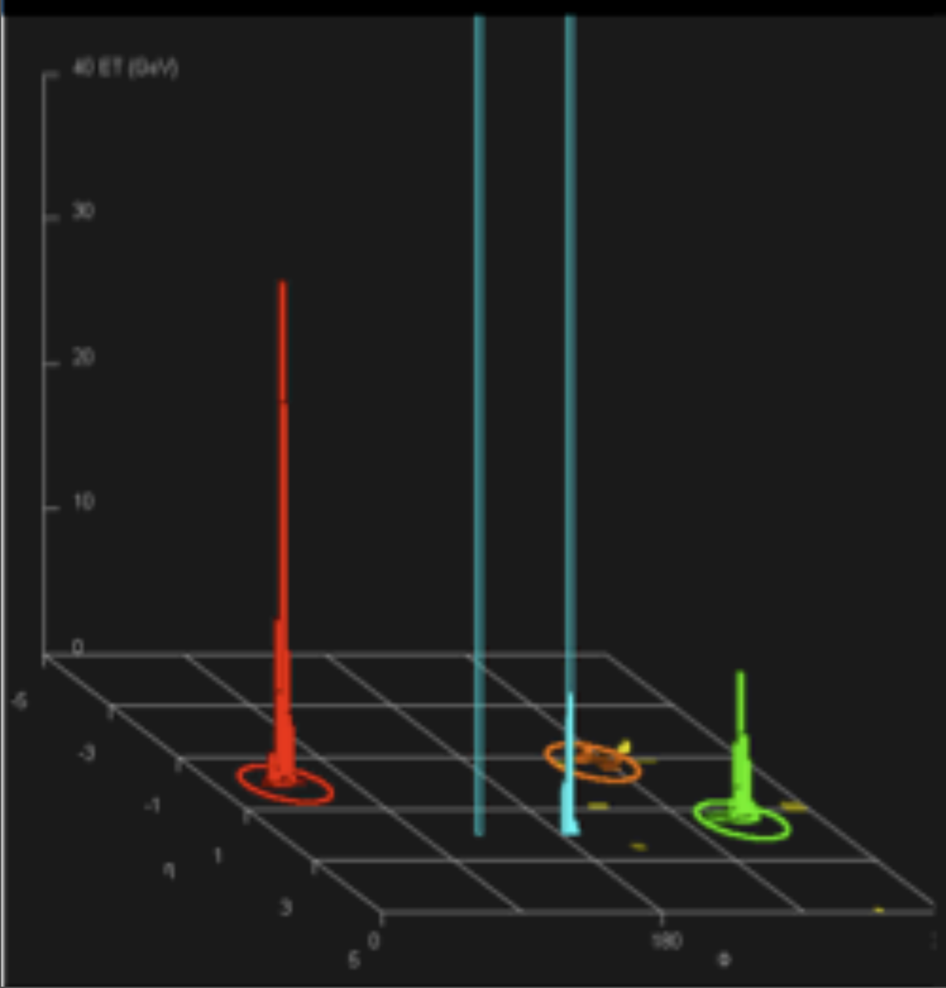
- It is usual to represent deposit of energy in the (η,φ) plane

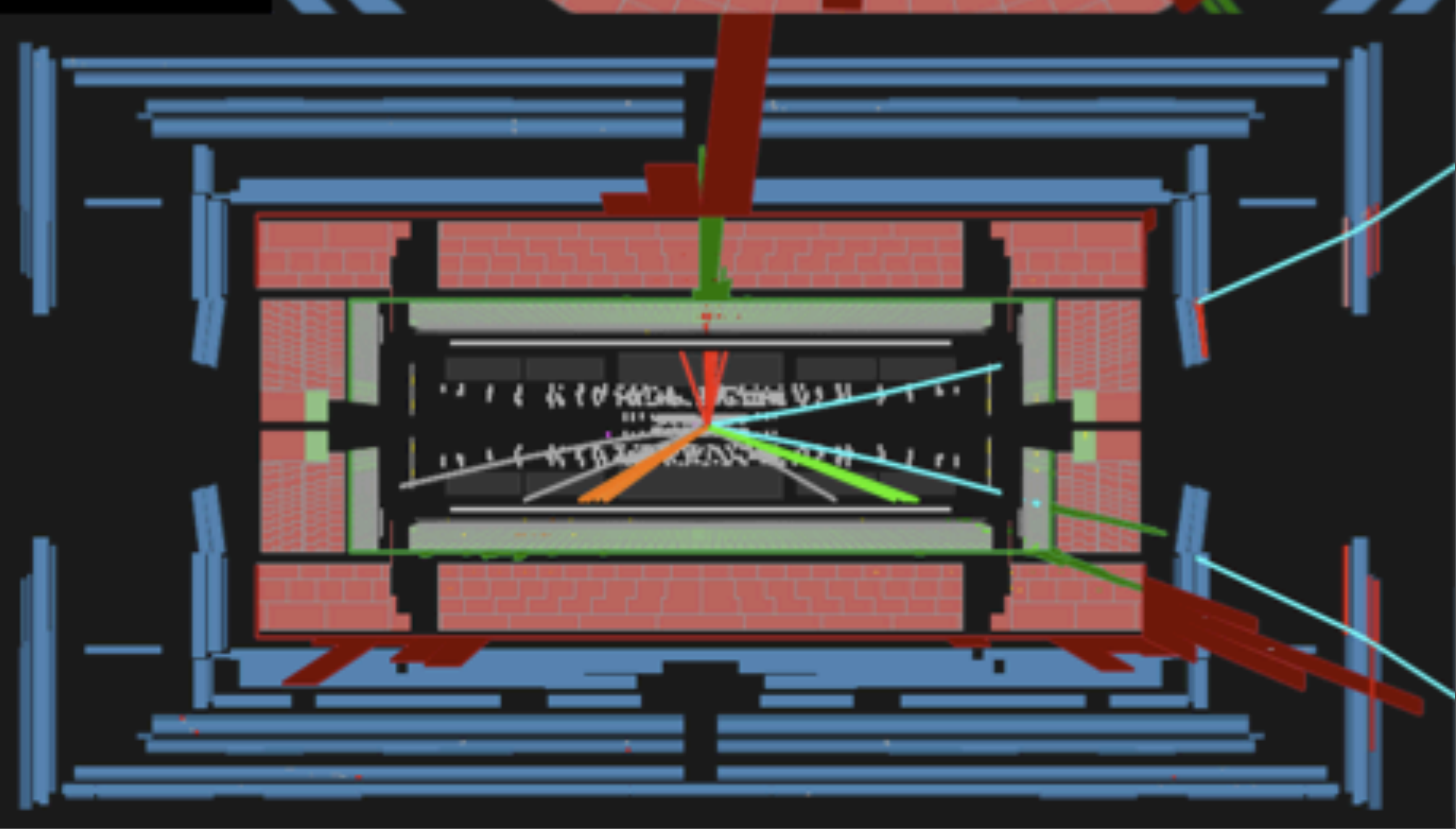
and the separation $\mathbf{\Delta R} = \sqrt{\mathbf{\Delta}\varphi^{\mathbf{2}} + \mathbf{\Delta}\eta^{\mathbf{2}}}$

ATLAS EXPERIMENT

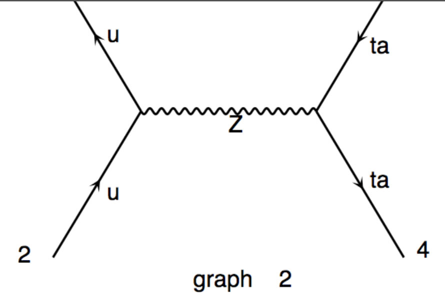
$$Z \rightarrow \mu^- \mu^+ + 3 \text{ jets}$$

Run Number 158466, Event Number 4174272
Date: 2010-07-02 17:49:13 CEST





Invariant mass



- Consider an unstable particle ($\mathbf{X} = \mathbf{Z},\ \mathbf{W}^{\pm},\ \mathbf{t}$) decaying $\mathbf{X} \to \mathbf{ab}\ldots$

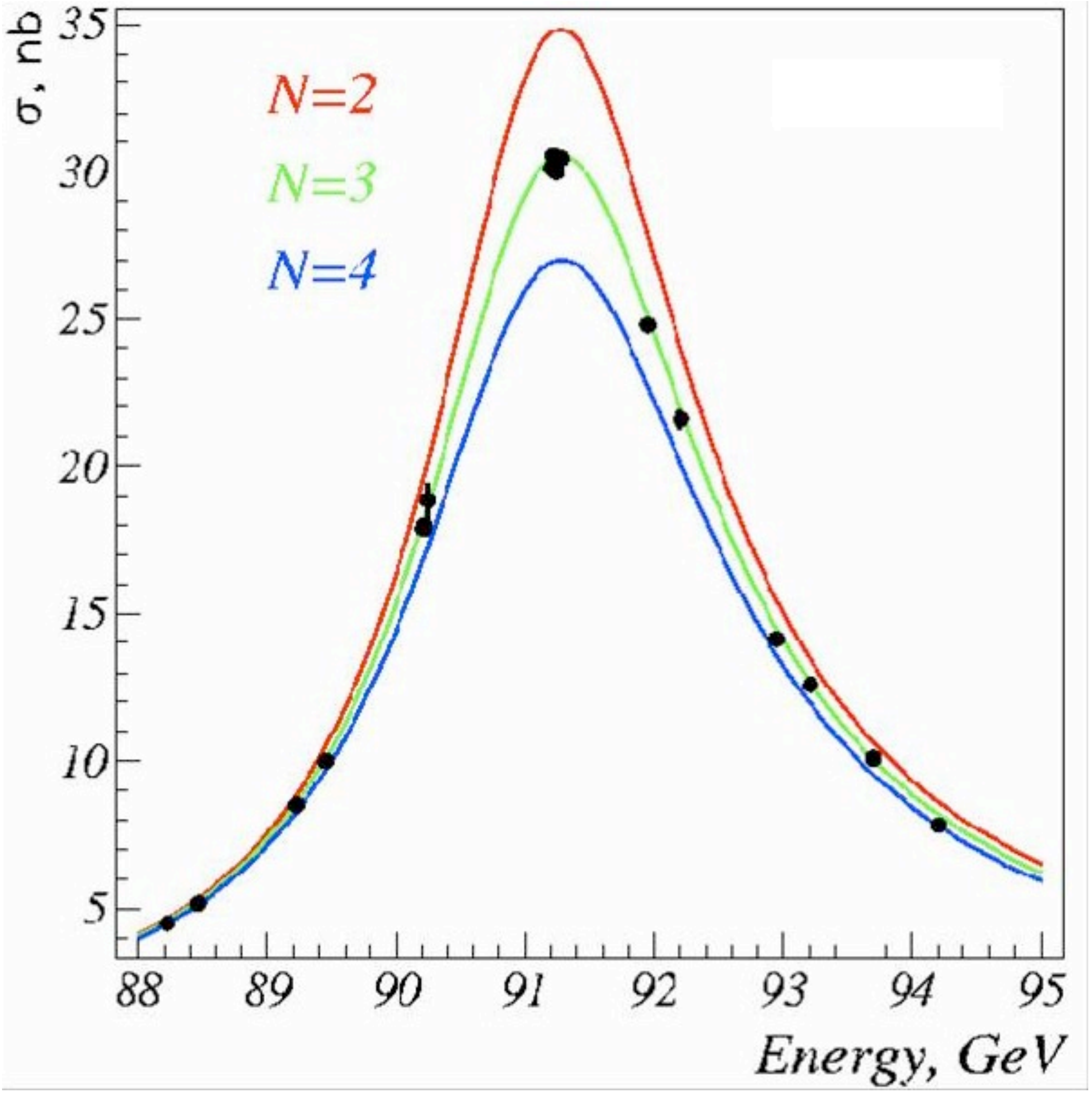
$$\frac{\mathbf{d}\sigma}{\mathbf{dM_{ab\ldots}}} \propto \frac{\mathbf{1}}{(\mathbf{M^2_{ab\ldots}} - \mathbf{M^2_X})^{\mathbf{2}} + \mathbf{\Gamma^2_X M^2_X}}$$

and exhibits a peak for $\mathbf{M^2_{ab\ldots}} = (\mathbf{p_a} + \mathbf{p_b} + \ldots)^{\mathbf{2}} = (\ \sum_{\mathbf{i}}^{\mathbf{n}} \mathbf{p_i}\ )^{\mathbf{2}} \approx \mathbf{M^2_X}$

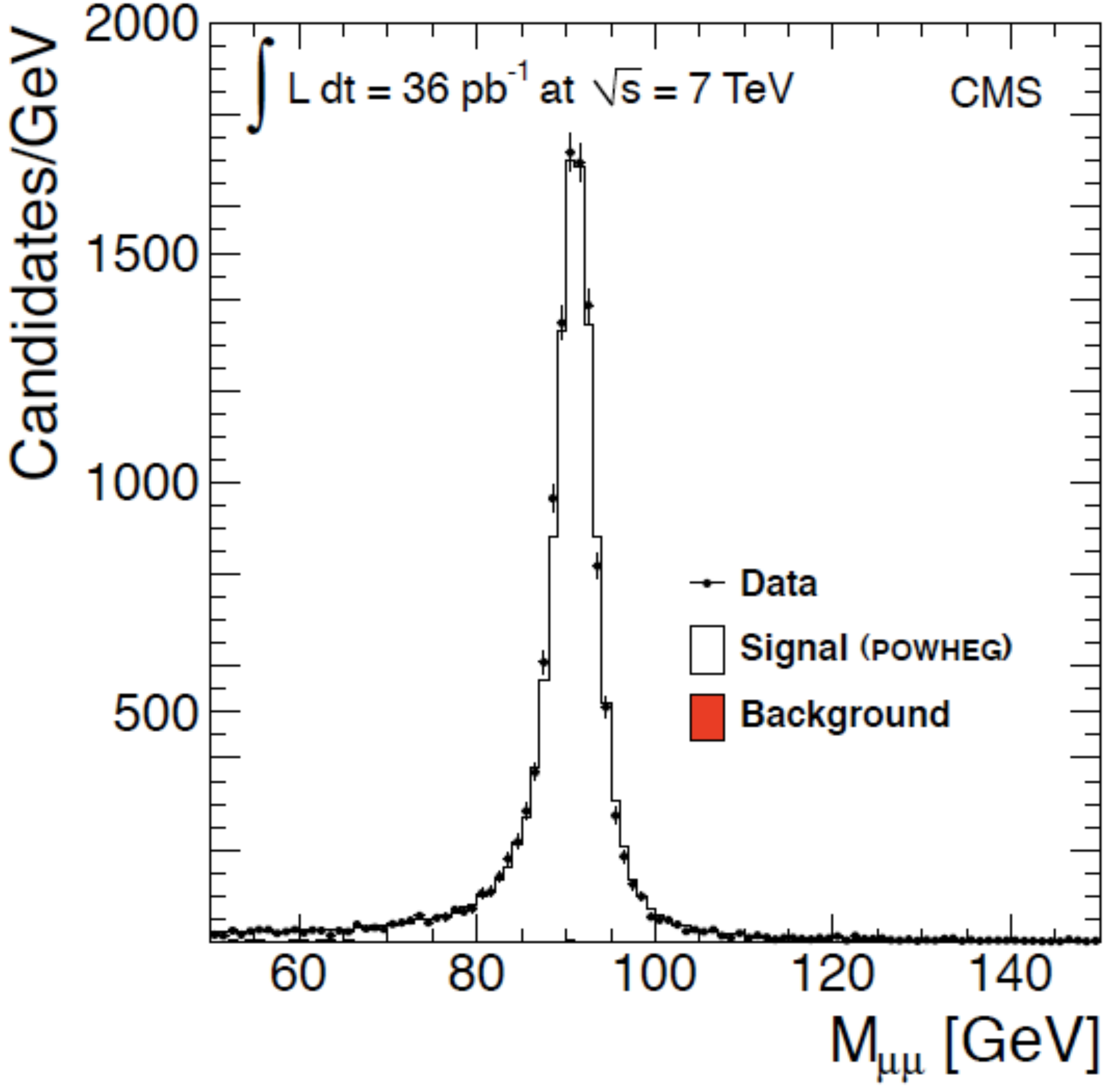
- For the same reason the production $\mathbf{ab} \to \mathbf{X}+$ anything exhibits a peak for $\mathbf{M^2_{ab}} \simeq \mathbf{M^2_X}$

- If the decays products are observable $\Longrightarrow$ we can reconstruct $\mathbf{M_{ab\ldots}}$, e.g. $\mathbf{Z} \to \mathbf{e^+e^-},\ \mathbf{b\bar{b}},\ \ldots$

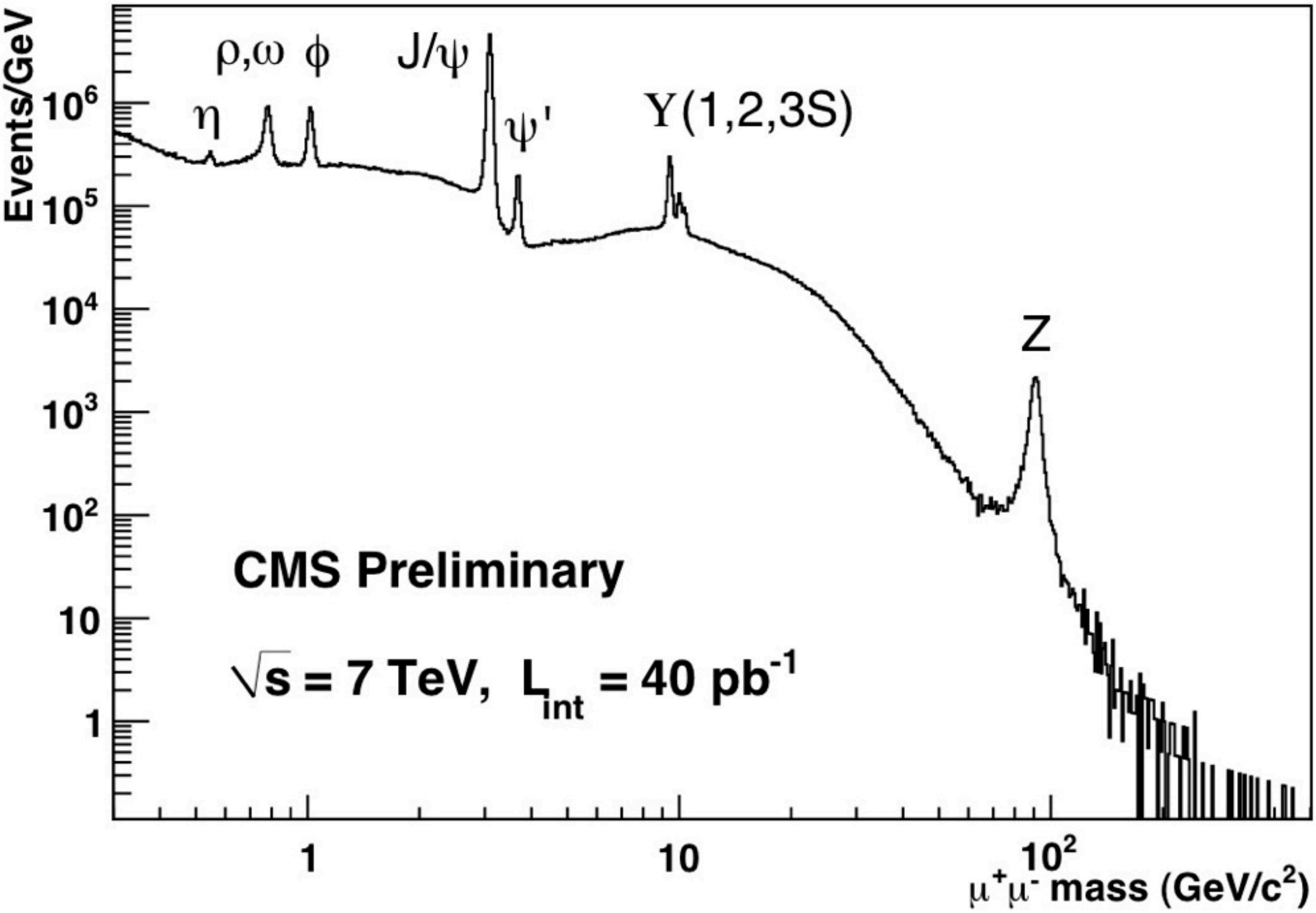
• $\mathbf{e^+e^- \to Z}$: in this case $\mathbf{M_{e^+e^-} = \sqrt{s}}$



- At the CMS $pp \to \mathbf{Z} + \mathbf{X} \to \mu^+\mu^-$



much more can be done with dileptons!



Events/GeV
10^6
10^5
10^4
10^3
10^2
10
1
η
ρ,ω
φ
J/ψ
ψ'
Υ(1,2,3S)
Z
CMS Preliminary
$\sqrt{s}$ = 7 TeV, L_{int} = 40 pb^{-1}
1
10
10^2
$\mu^+\mu^-$ mass (GeV/c^2)

Transverse mass

- Consider the process $\mathbf{p\bar{p} \to WX \to e\nu X}$

$$\mathbf{m^2_{e\nu} = (E_e + E_\nu)^2 - (\tilde{p}_{eT} + \tilde{p}_{\nu T})^2 - (p_{ez} + p_{\nu z})^2} \;.$$

However, $\tilde{\mathbf{p}}_\nu$ is not observable.

- We can infer $\vec{p}_{\nu T} \simeq \tilde{\not{p}}_T = -\sum \tilde{\mathbf{p}_T}$ (observed). Analogously $\not{E}_T = \mathbf{E}_\nu$

uses all we can measure in the transverse plane

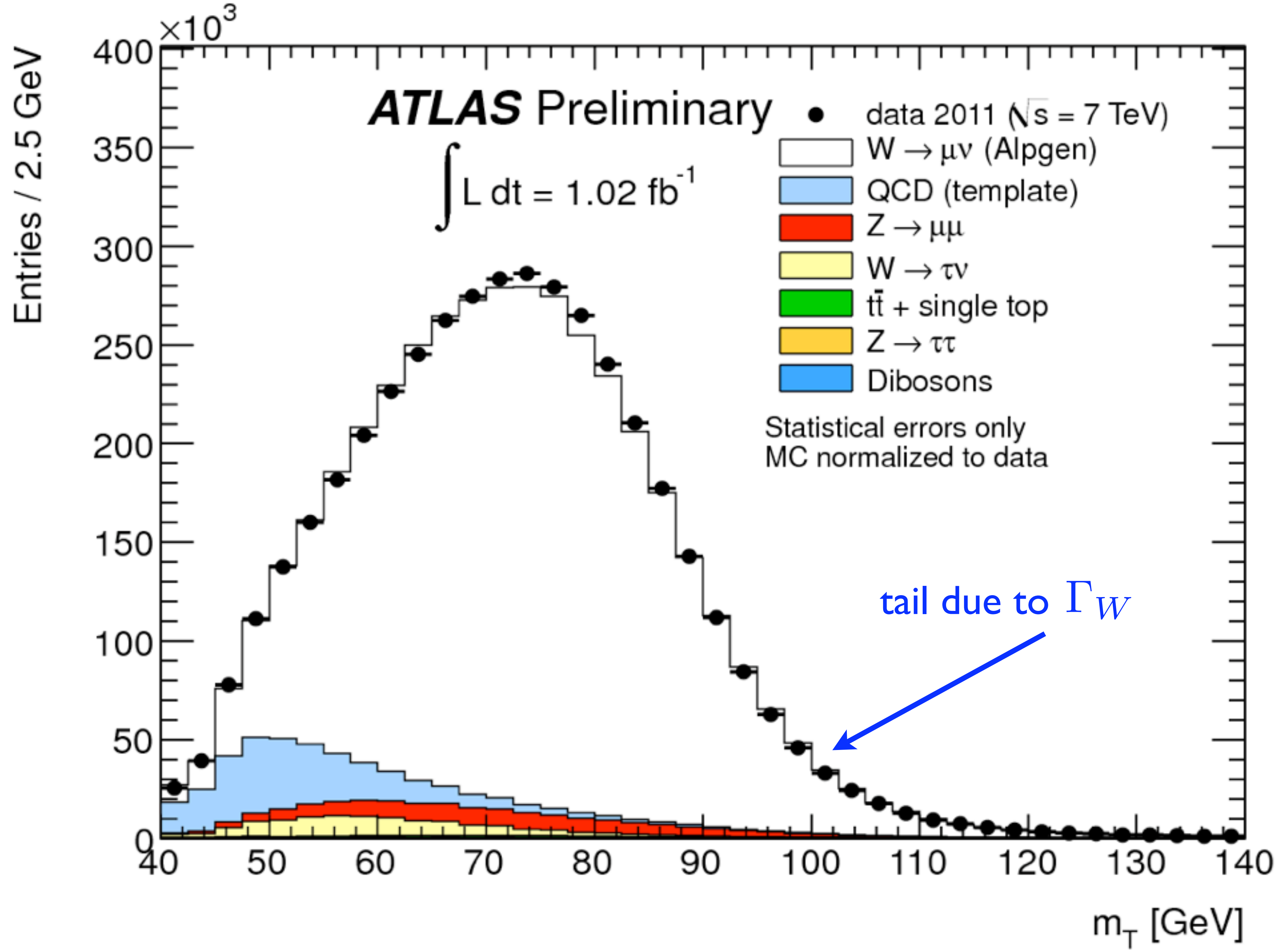
- We define the transverse mass [UA1]

$$\mathbf{m^2_{e\nu T} \equiv (E_{eT} + E_{\nu T})^2 - (\tilde{p}_{eT} + \tilde{p}_{\nu T})^2 \approx 2\tilde{p}_{eT} \cdot \tilde{p}_{\nu T} \approx 2E_{eT}} \not{E}_T (\mathbf{1} - \cos\phi_{\mathbf{e\nu}})$$

- In general $\mathbf{0 \le m_{e\nu T} \le m_{e\nu}}$ (Prove it!)

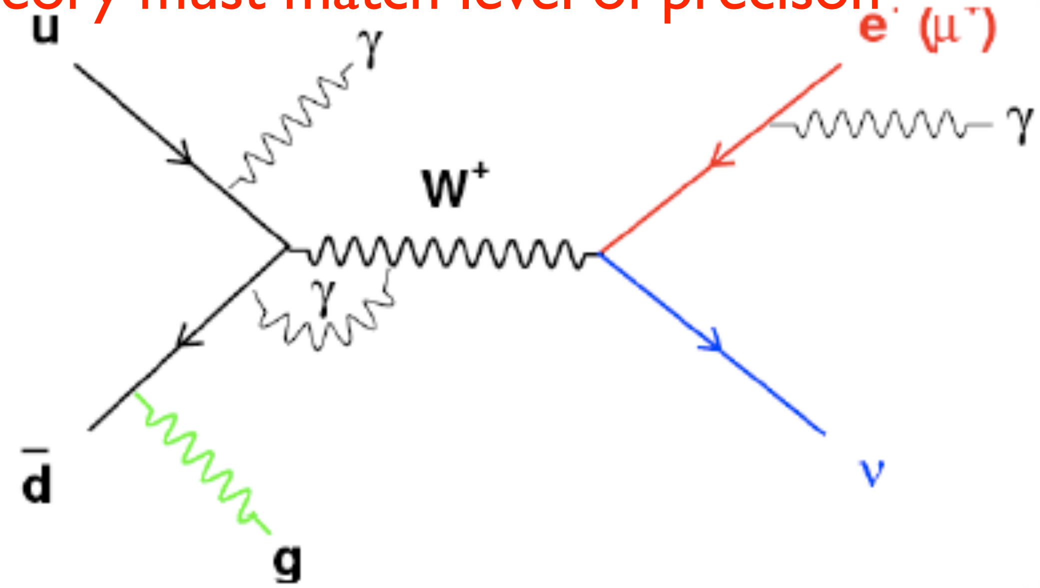
• For $q\bar{q}' \to W^* \to e\nu$ there is a Jacobian peak.

$$\frac{\mathbf{d}\hat{\sigma}}{\mathbf{dm^2_{e\nu,T}}} \propto \frac{\mathbf{\Gamma_W M_W}}{\mathbf{(m^2_{e\nu} - M^2_W)^2 + \Gamma^2_W M^2_W}} \frac{\mathbf{1}}{\sqrt{\mathbf{m^2_{e\nu} - m^2_{e\nu,T}}}}.$$



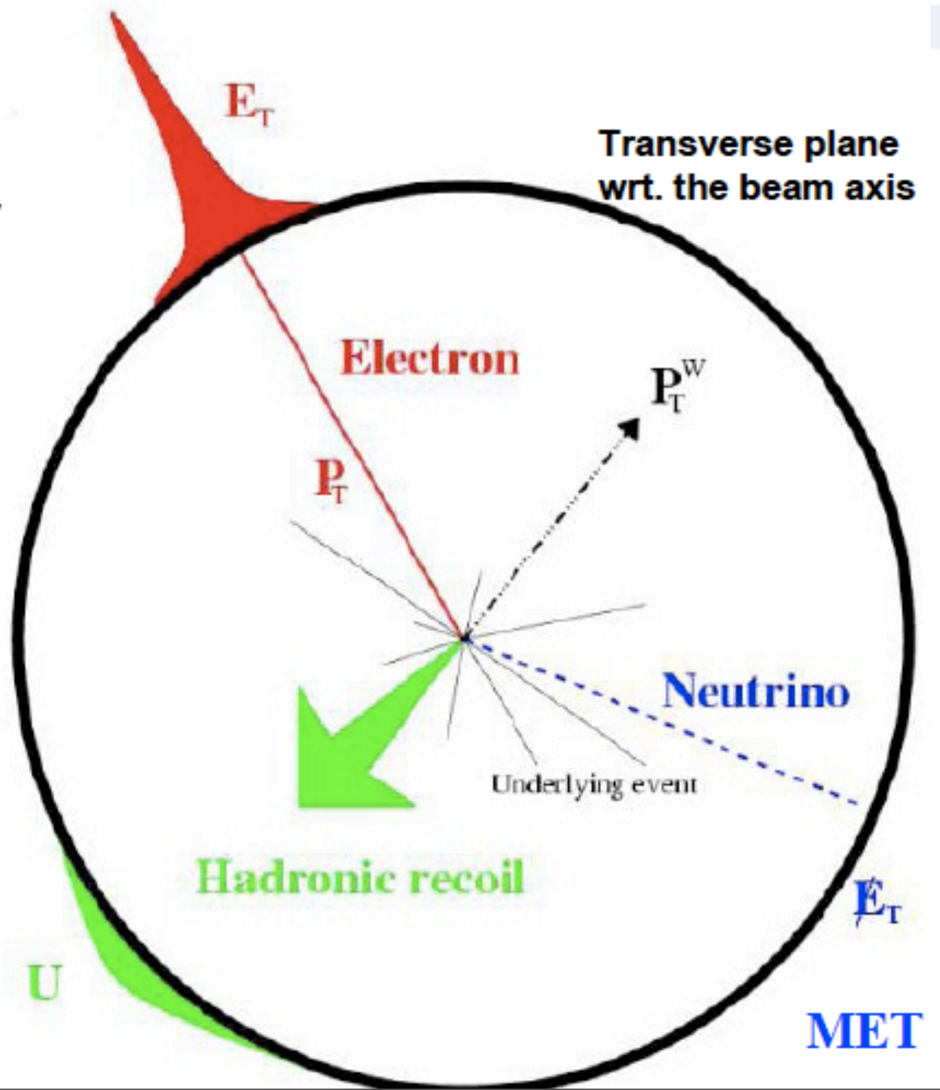
W mass at hadron colliders

theory must match level of precison



W signature:

- Isolated high-p_T e/μ
- missing E_T



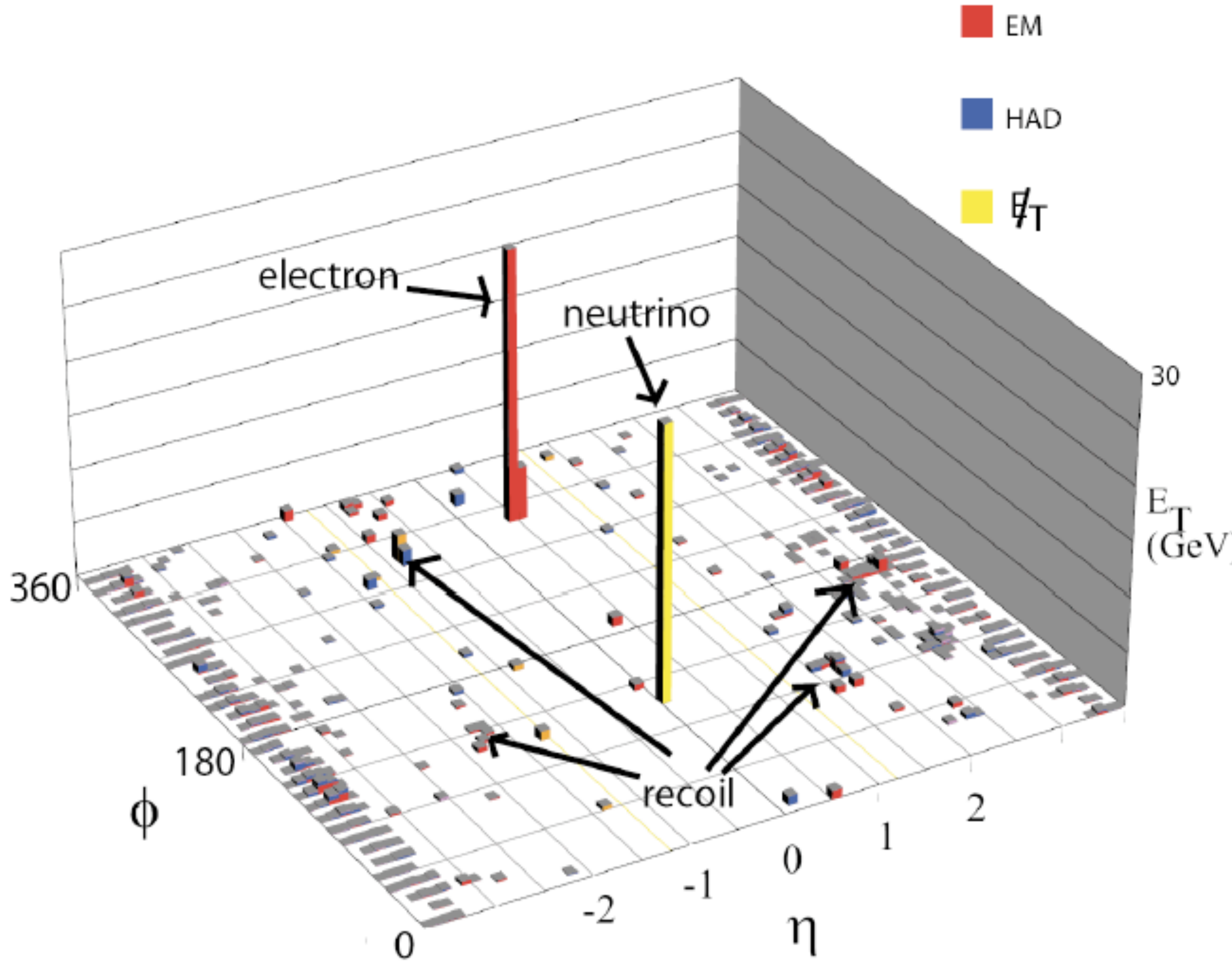
W mass at hadron colliders

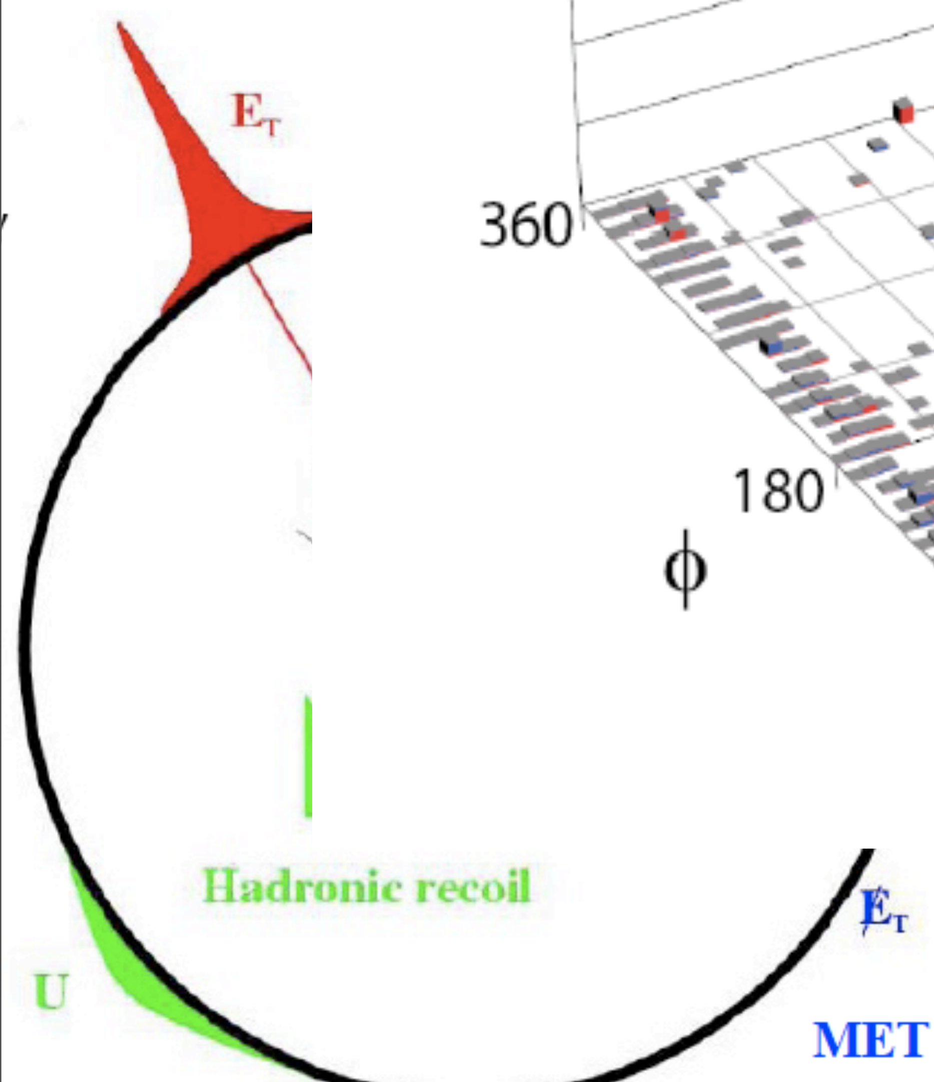
theory must match level of precison

W sigr

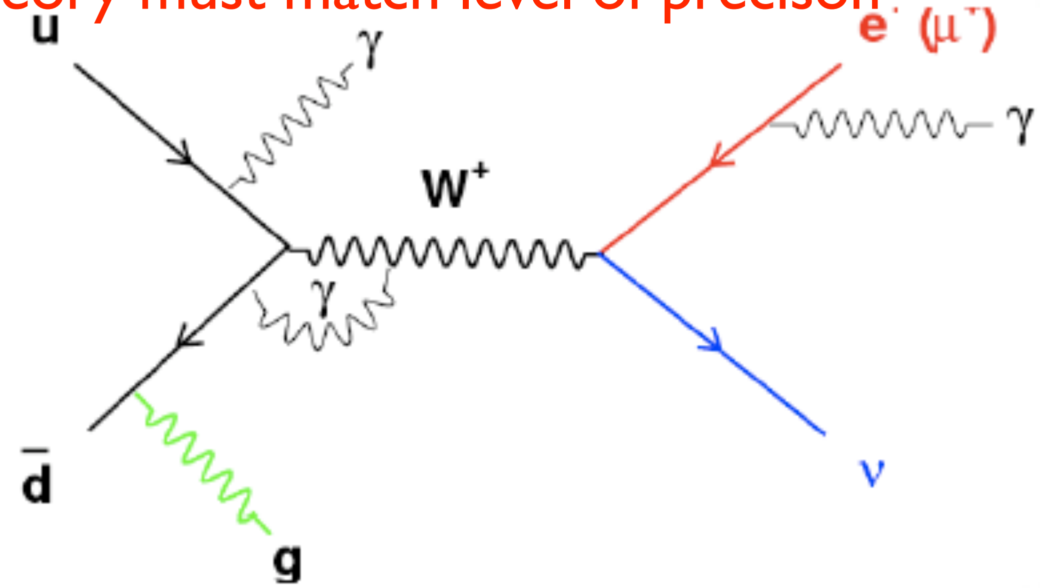
- Isolat

- missi





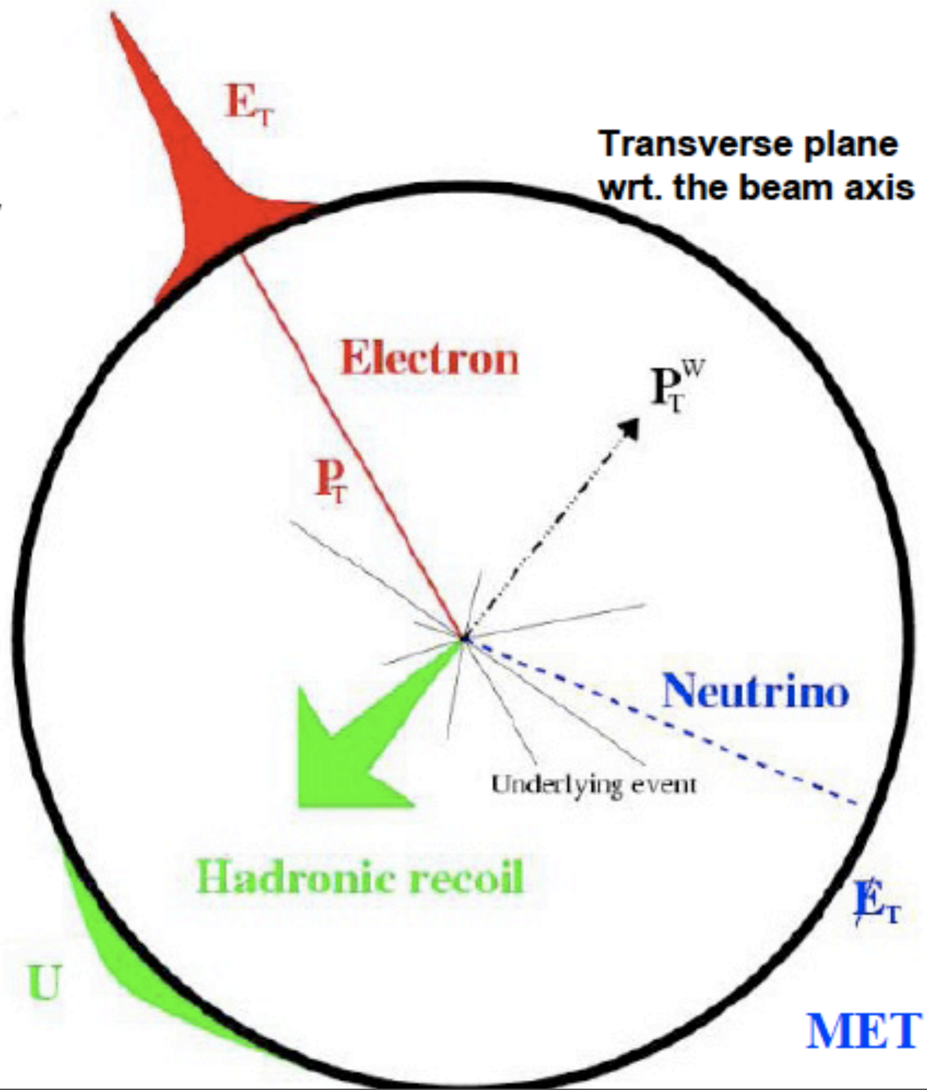
W mass at hadron colliders



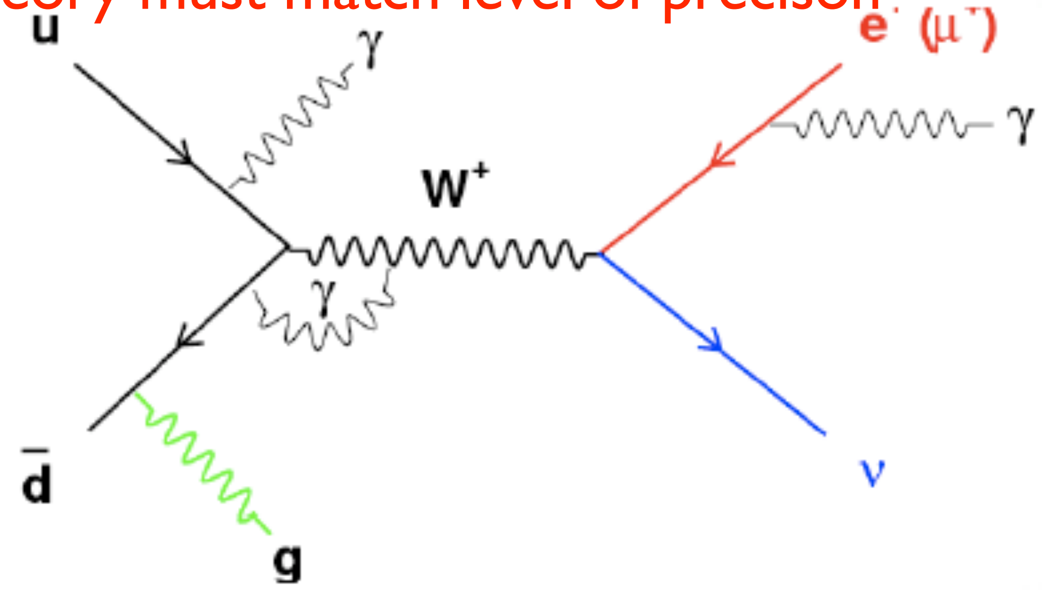
W signature:

- Isolated high-p_T e/μ

- missing E_T



theory must match level of precison



W mass at hadron colliders

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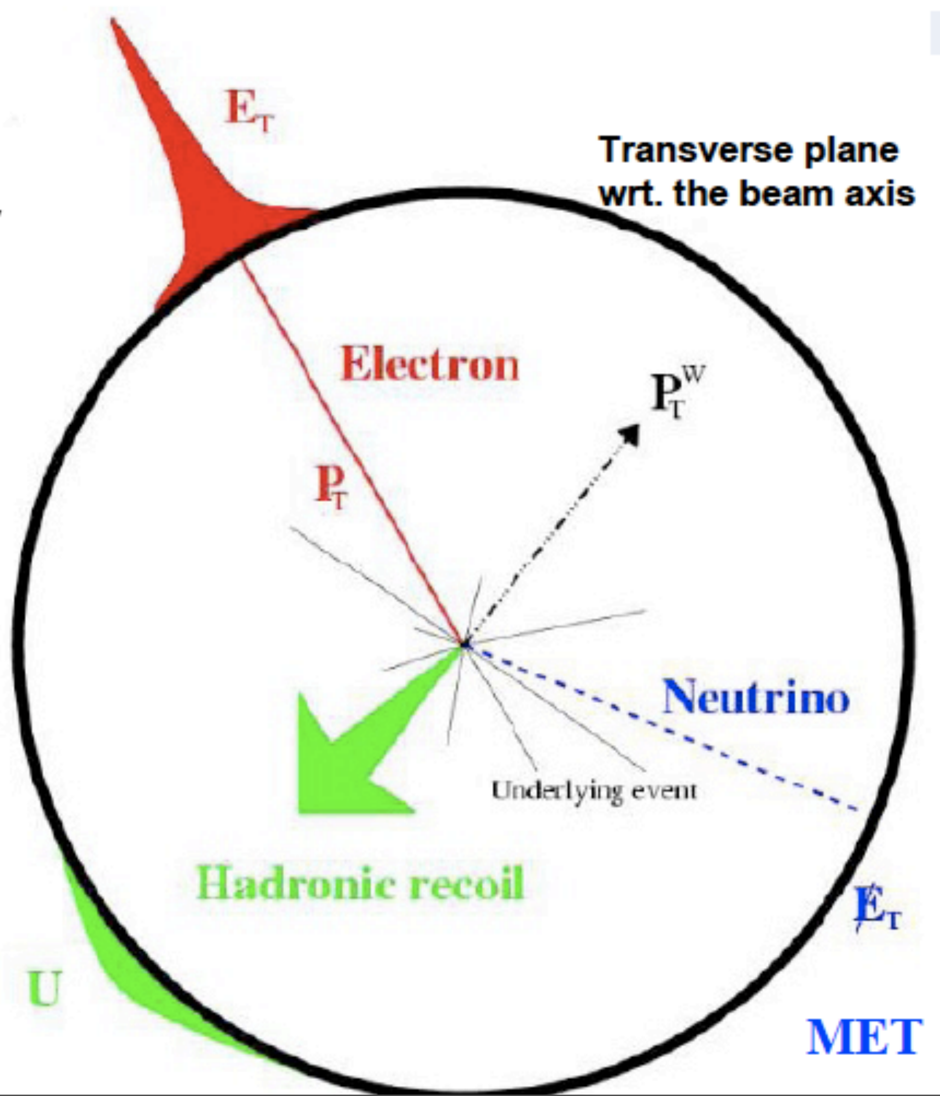


Main backgrounds:

- QCD multijet

- $Z \rightarrow \ell\ell$

- $W \rightarrow \tau\nu \rightarrow \ell\nu\nu\nu$

Kinematical variables:

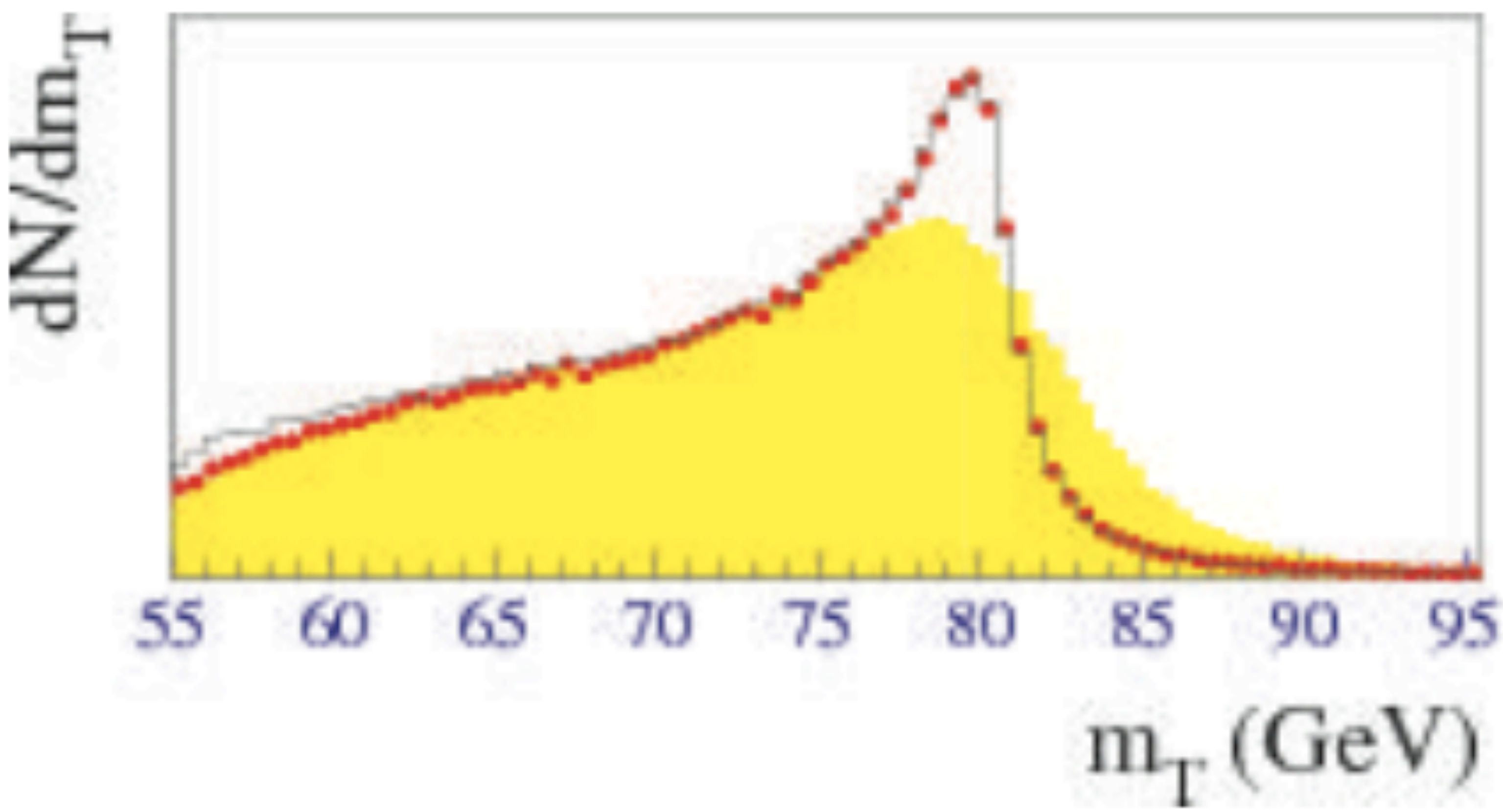
- transverse mass

$$m_T = \sqrt{2E_T^\ell \not{E}_T (1 - \cos\varphi_{\ell\nu})}$$

- lepton transverse momentum
- $\not{E}_T$

Kinematical variables:

- trans
  m_T
- lepto
- $\not{E}_T$



❄ Rather insensitive to $\vec{p}_W$

❄ m_T has a significant resolution sensitivity

Kinematical variables:

- transverse mass

$$m_T = \sqrt{2E_T^{\ell}\not{E}_T(1-\cos\varphi_{\ell\nu})}$$

- lepton transverse momentum
- $\not{E}_T$

Kinematical variables:

- transverse mass

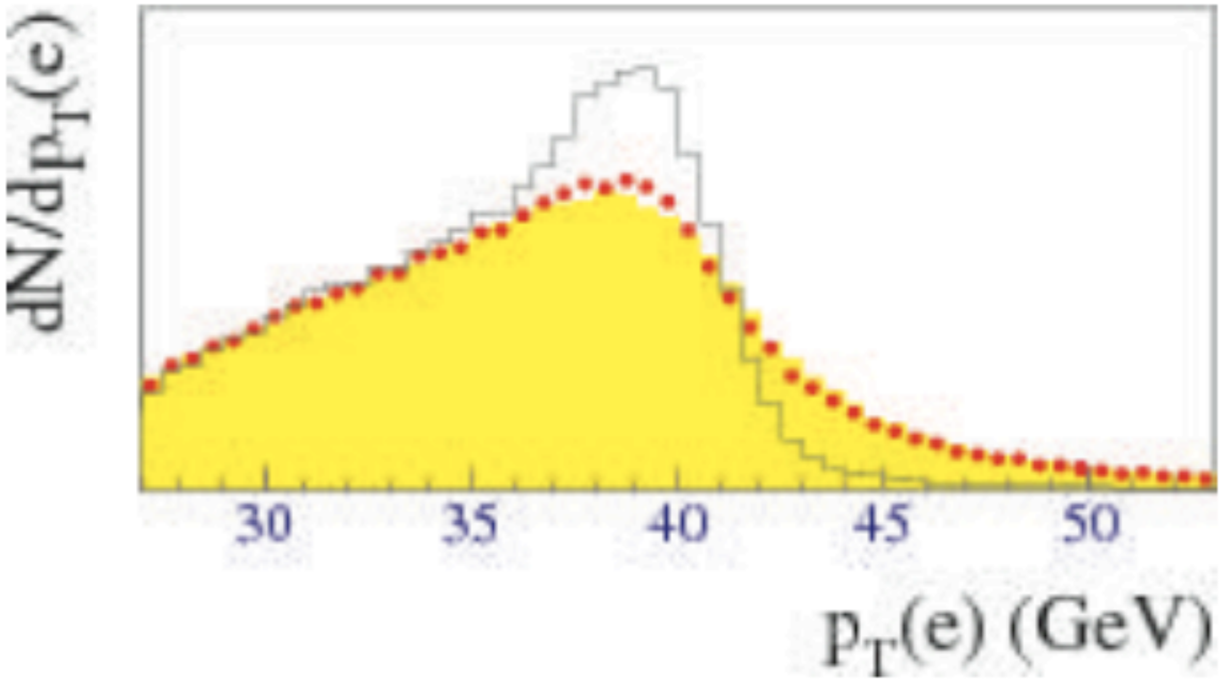
m_T

- lepto

- $\not{E}_T$

$$\frac{d\hat{\sigma}}{dp_{eT}} = \frac{4p_{eT}}{\hat{s}\sqrt{1-4p_{eT}^2/\hat{s}}} \frac{d\hat{\sigma}}{d\cos\theta^*}$$

there is a Jacobian peak at $p_{eT} = M_W/2$



- small detector smearing effect
- significant p_T^W effect

Kinematical variables:

- transverse mass

$$m_T = \sqrt{2E_T^\ell \not{E}_T (1 - \cos\varphi_{\ell\nu})}$$

- lepton transverse momentum

- $\not{E}_T$

Kinematical variables:

- transverse mass

$$m_T = \sqrt{2E_T^{\ell} \not{E}_T (1 - \cos\varphi_{\ell\nu})}$$

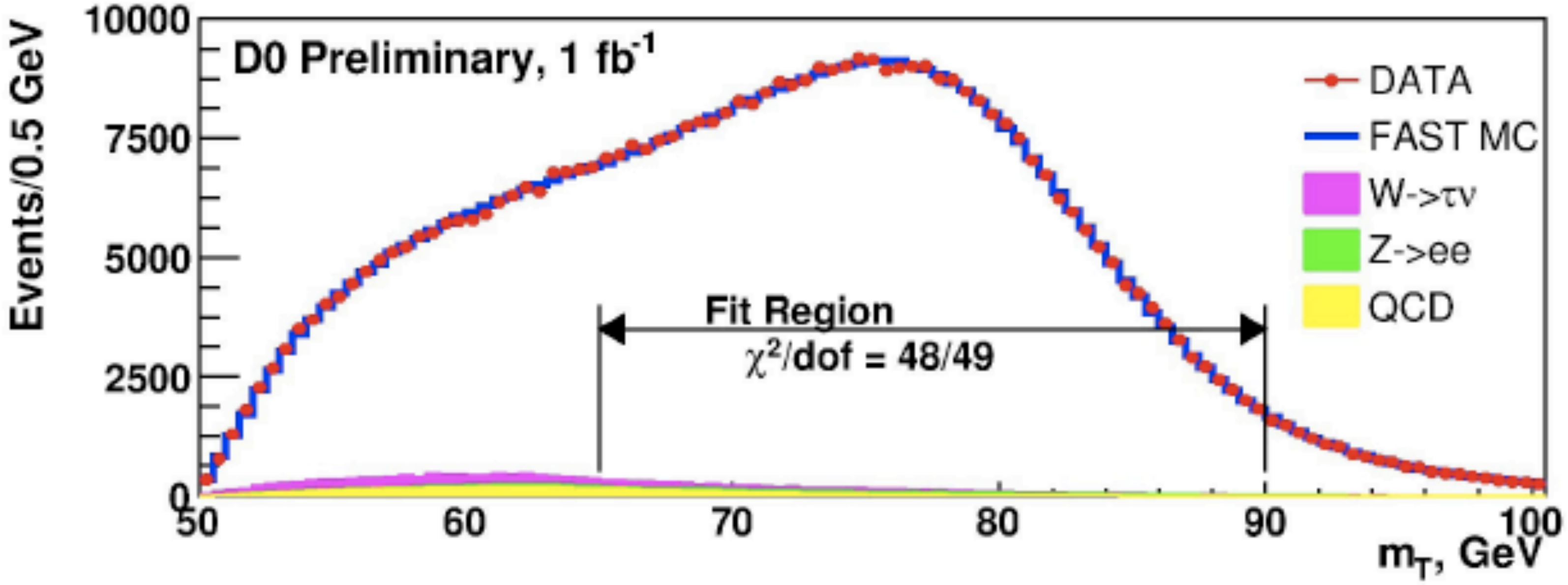
- lepton transverse momentum
- $\not{E}_T$

D0 event selection:

- $P_T^e > 25$ GeV
- $|\eta_e| < 1.05$
- $\not{E}_T > 25$ GeV
- $50 < m_T < 200$ GeV
- $E_T^{had} < 15$ GeV

M_W and Γ_W are measured fitting the distributions

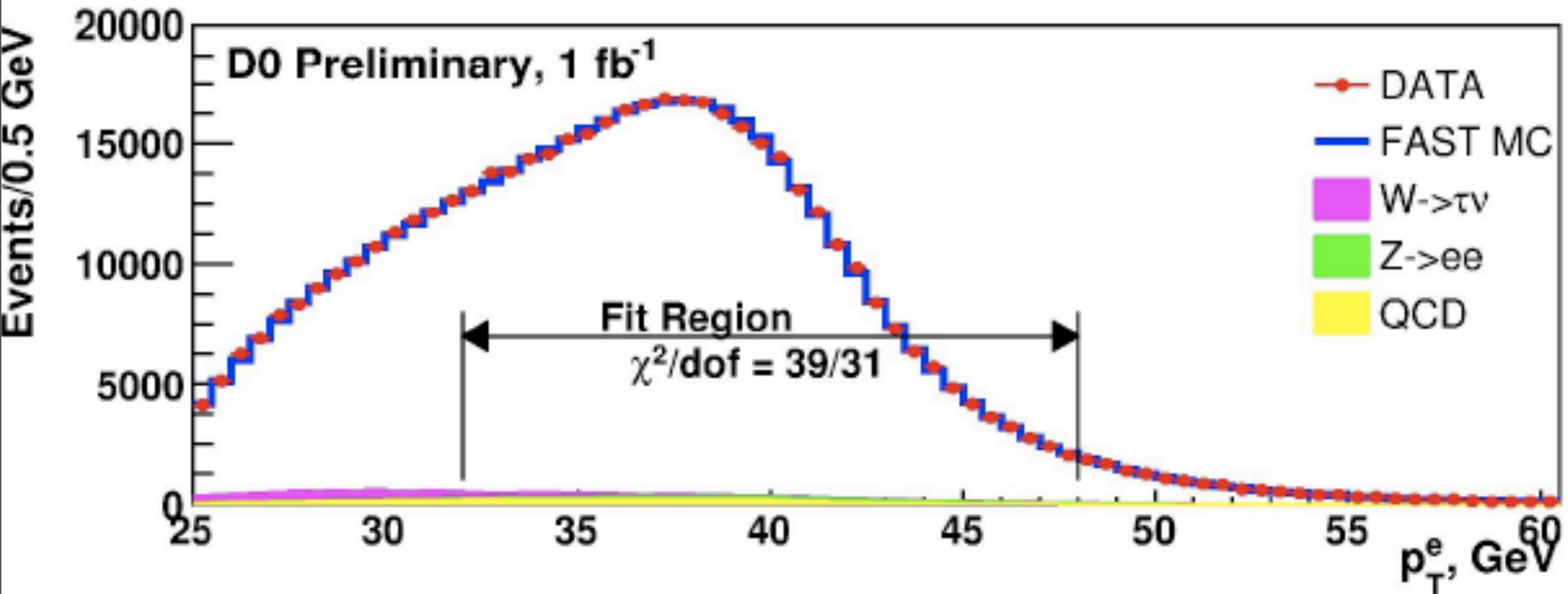
m_T method



m_W = 80.401 ± 0.023 GeV (stat)

Fit range: $65 < m_T < 90$ GeV

Electron p_T method

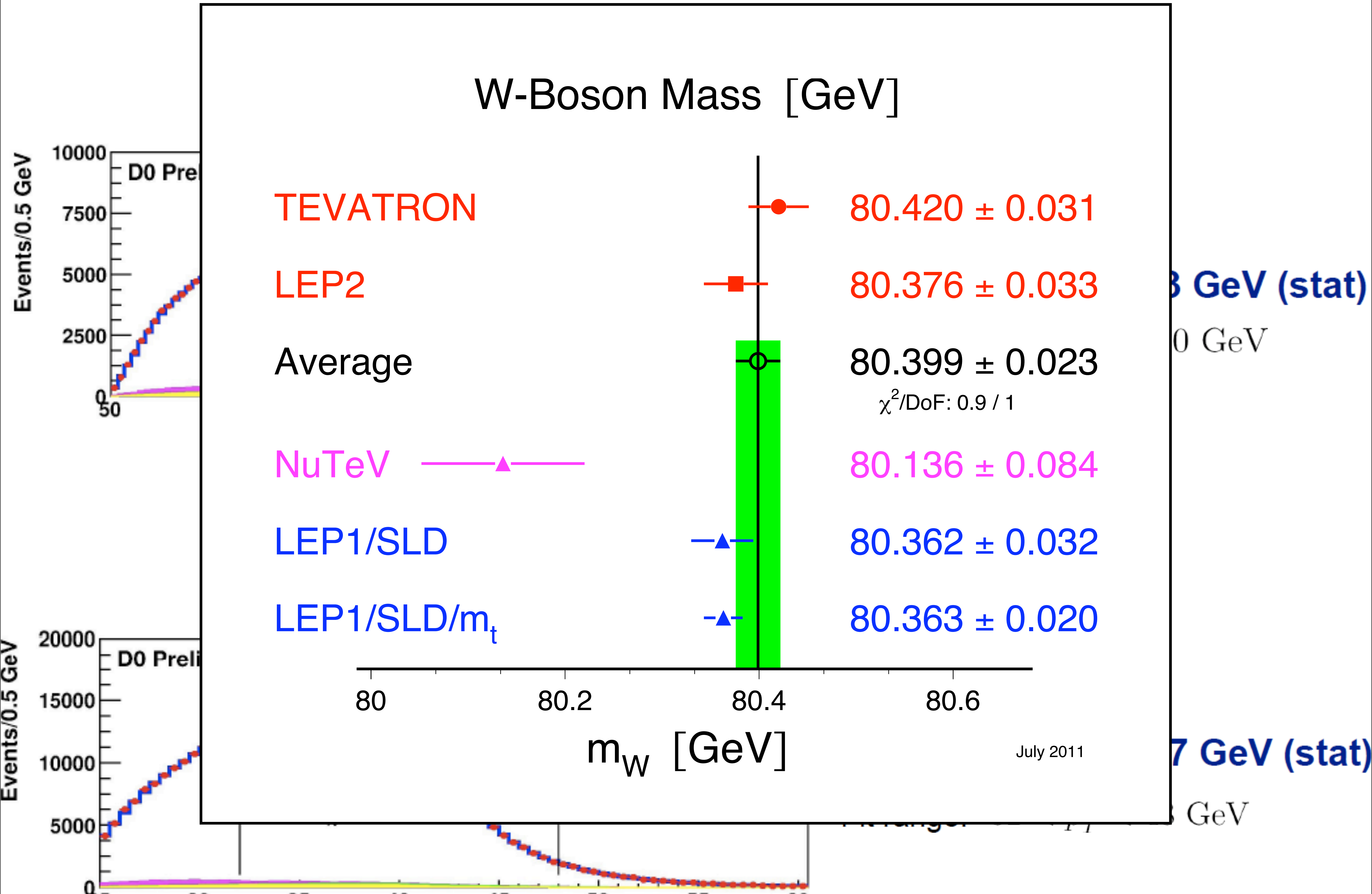


m_W = 80.400 ± 0.027 GeV (stat)

Fit range: $32 < p_T^e < 48$ GeV

[Cwiok]

M_W and Γ_W are measured fitting the distributions



[Cwiok]

M_W and Γ_W are measured fitting the distributions

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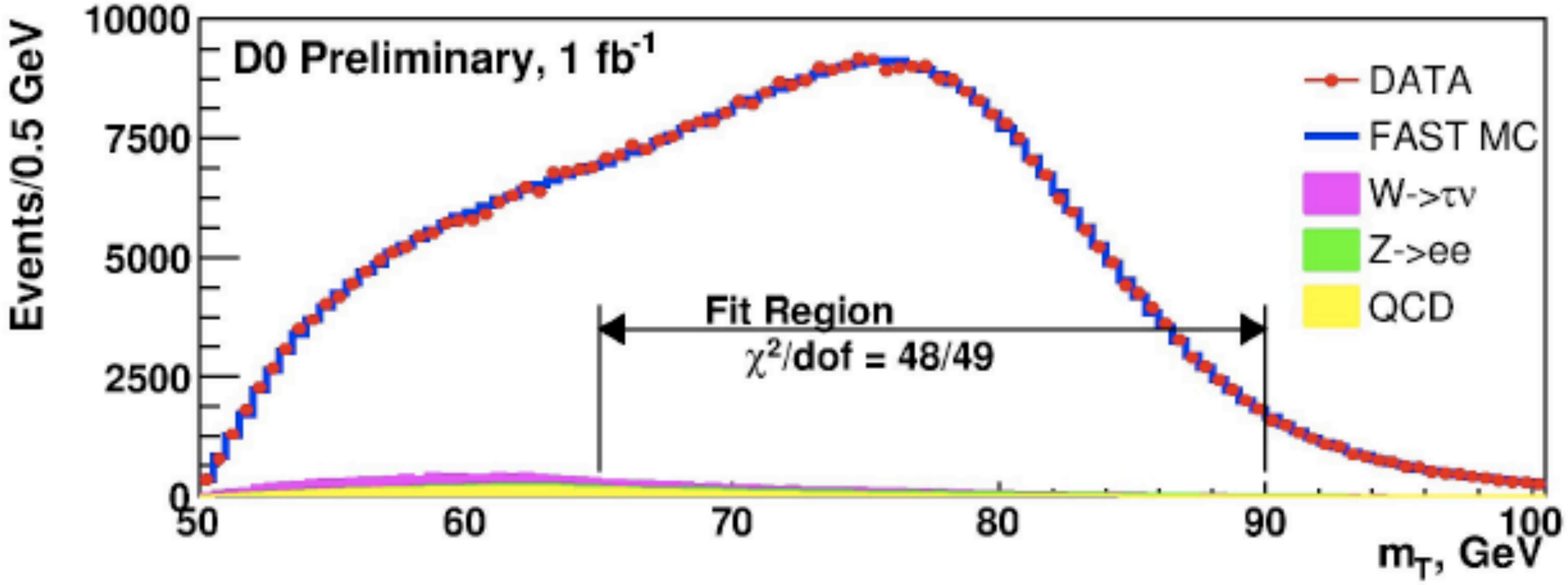

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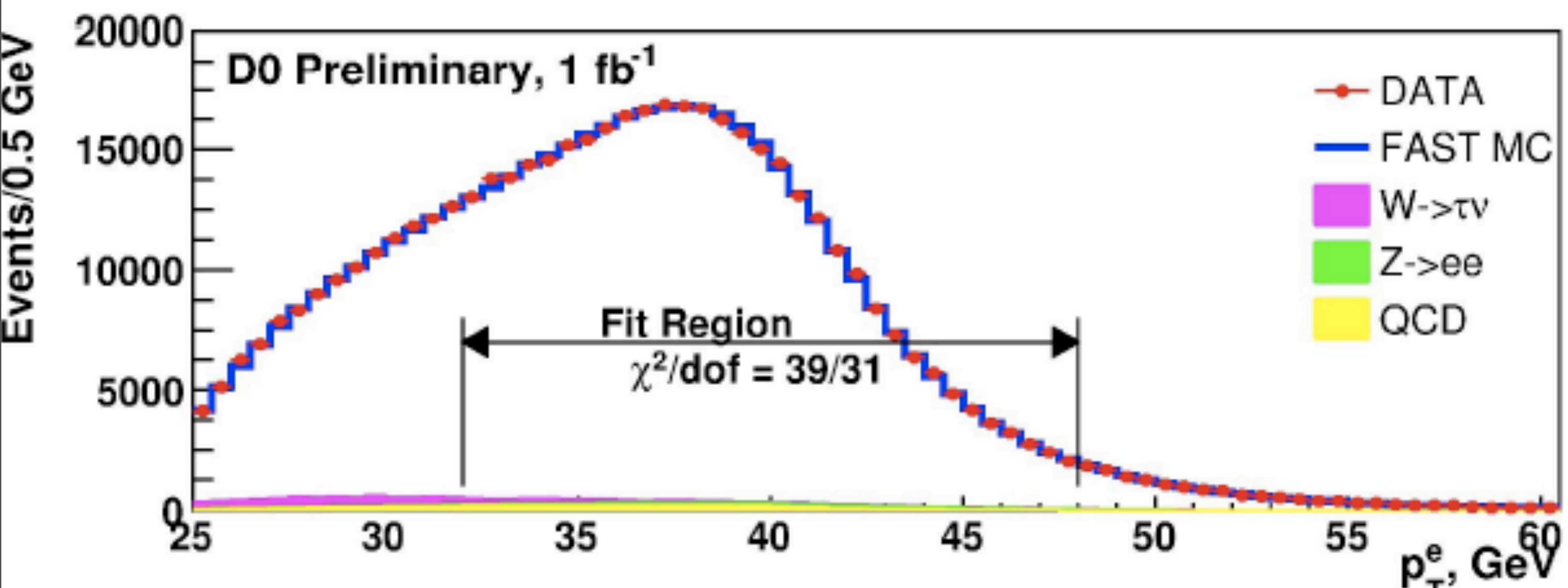

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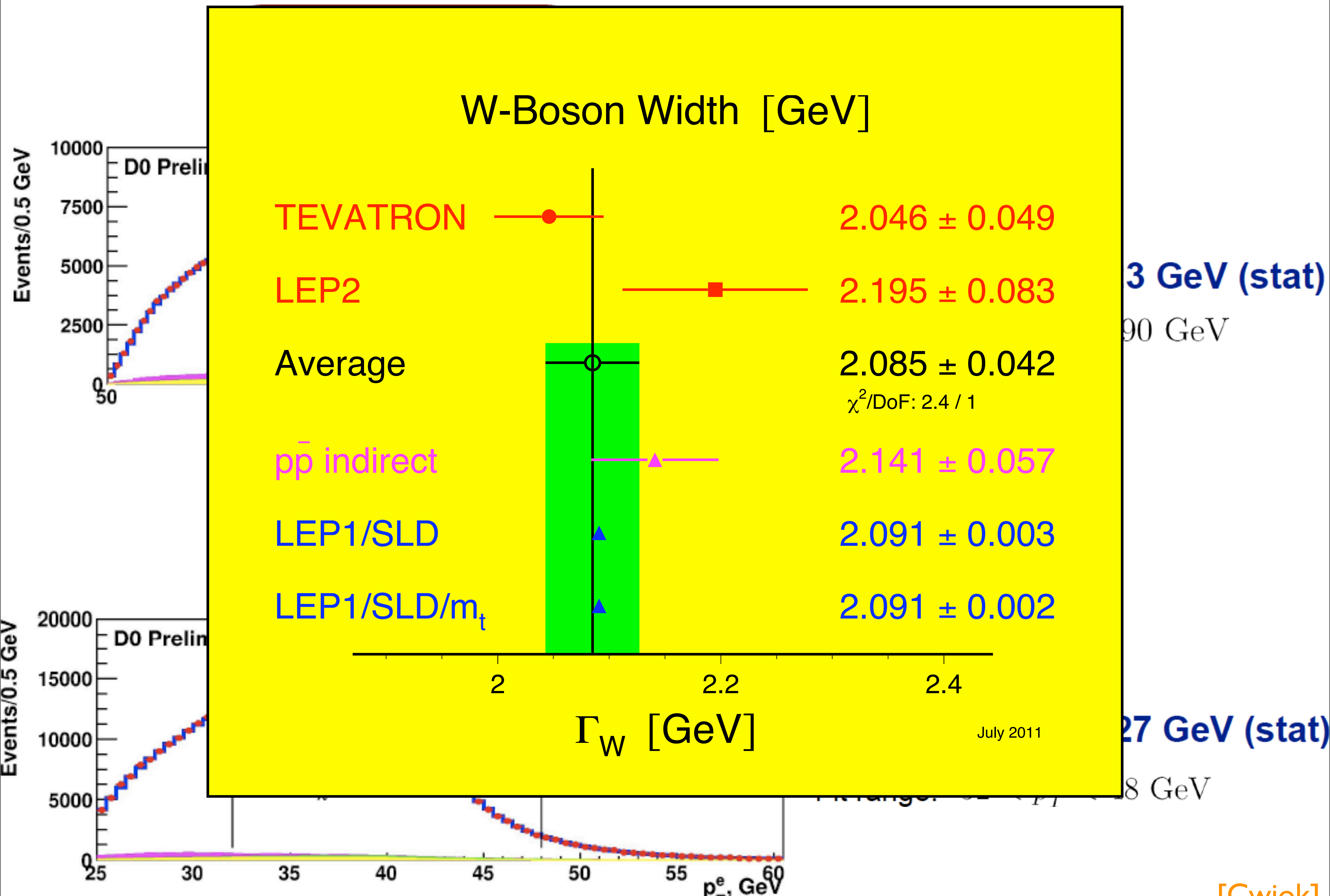
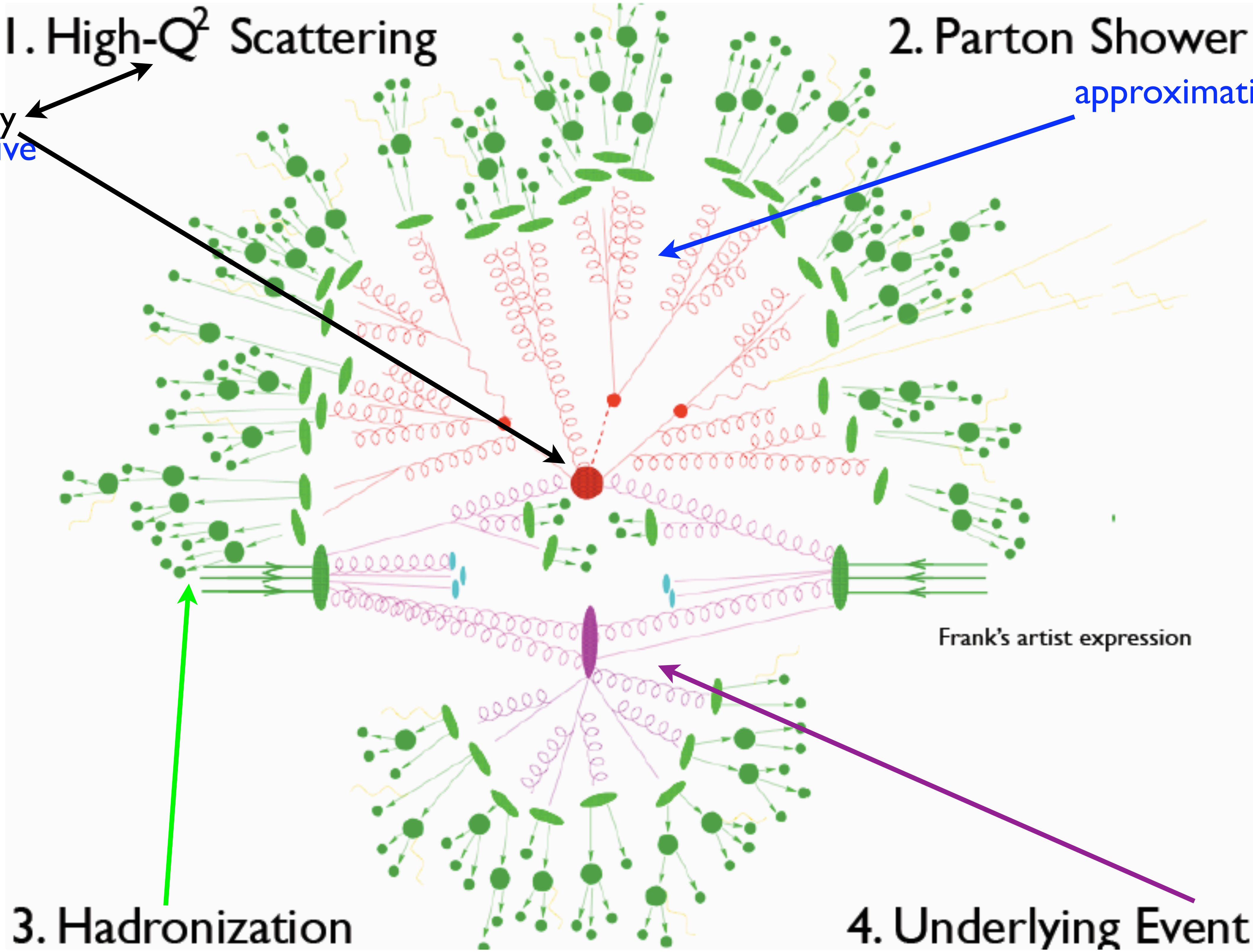


[Cwiok]

Motivation:

"Elements" of a collision



field theory
very inclusive

approximation

model

model

VI. Cross section evaluation

- Evaluating cross section in a hadron-hadron machine requires

$$\sigma = \int dx_1 dx_2 \sum_{\text{subp}} f_{a_1/p}(x_1)\, f_{a_2/\bar{p}}(x_2)$$

$$\frac{1}{2\hat{s}(2\pi)^{3n-4}} \int d\Phi_n(x_1 P_A + x_2 P_B;\, p_1 \ldots p_n)\Theta(\text{cuts}) \overline{\sum} |\mathcal{M}|^2 (a_1 a_2 \to b_1 \ldots b_n)$$

phase space integration

scattering amplitude

we need to evaluate as precisely as we can the cross section

Phase space

(art/science)

- The sum of final states is

$$d\Phi_n(ab \to 1 \ldots n) \equiv \delta^4(p_a + p_b - p_1 - \ldots - p_n) \prod_{i=1}^{n} \frac{d^3\vec{p}_i}{2E_i}$$

Lorentz invariant

- $3n - 4$ integrals.
- With azimuthal symmetry $\Longrightarrow$ $3n - 5$ integrals
- In a hadron collider we have 2 extra integrals ($x_{1,2}$)

n	$3n - 3$
2	3
3	6
4	9
...	...
8	21

Scattering amplitude evaluation

- We also need to evaluate $\overline{\sum}|\mathcal{M}|^2(a_1a_2 \to b_1 \dots b_n)$ with $\mathcal{M} = \sum_{i=1}^{f} \mathcal{M}_i$.
- If f (n) is large the "trace technique" becomes useless since we have to evaluate $f(f+1)/2$ cross terms Re($\mathcal{M}_i^* \mathcal{M}_j$).
- It then becomes advantageous to numerically evaluate $\mathcal{M}_i$ $\Longrightarrow$ complexity grows linearly with f.
- One efficient technique is to work in helicity basis

$$|\mathcal{M}|^2 = \sum_{\lambda_a \dots \lambda_n} |\mathcal{M}(\lambda_a \dots \lambda_n)|^2$$

- For fermions

in the representation $\gamma_5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$ we write $\psi = \begin{pmatrix} \psi_- \\ \psi_+ \end{pmatrix}$

where ψ_- and ψ_+ are Weyl spinors of negative and positive helicity.

❄ For instance, u-spinor with chiral components $u(p,\sigma)_\pm = \sqrt{p^0 \pm \sigma|\mathbf{p}|}\,\chi_\sigma(p)$, where

$$\chi_+(p) = \frac{1}{\sqrt{2|\mathbf{p}|(|\mathbf{p}|+p_z)}} \begin{pmatrix} |\mathbf{p}|+p_z \\ p_x + ip_y \end{pmatrix} \ ; \ \chi_-(p) = \frac{1}{\sqrt{2|\mathbf{p}|(|\mathbf{p}|+p_z)}} \begin{pmatrix} -p_x + ip_y \\ |\mathbf{p}|+p_z \end{pmatrix}$$

❄ The HELAS package has all elements need to evaluate Feynman diagrams defined as fortran routines. For instance, an incoming $u(p, NH)$-spinor is given by a simple subroutine call,

```
call IXXXXX(P,FMASS,NH,+1,PSI)
```

to compute the spinor v change $+1 \to -1$.

❄ Outgoing spinors are generate by `call IXXXXX(P, FMASS, NH, ±1, PSI)`

❄ the polarization vector of incoming vector bosons is
`call VXXXXXX(P, VMASS, NHEL, −1, VC)`

❄ The package MADGRAPH can be used to generate SM and SUSY amplitudes!

- MADGRAPH can generate $2 \to 8$ processes

- MADGRAPH already sums over polarizations and colors

- MADGRAPH produces a ps file with the Feynman diagrams

- The package MADEVENT goes further and produces a complete Monte Carlo

- Interfaces for PYTHIA, HERWIG, and ROOT are available

`http://madgraph.hep.uiuc.edu/`