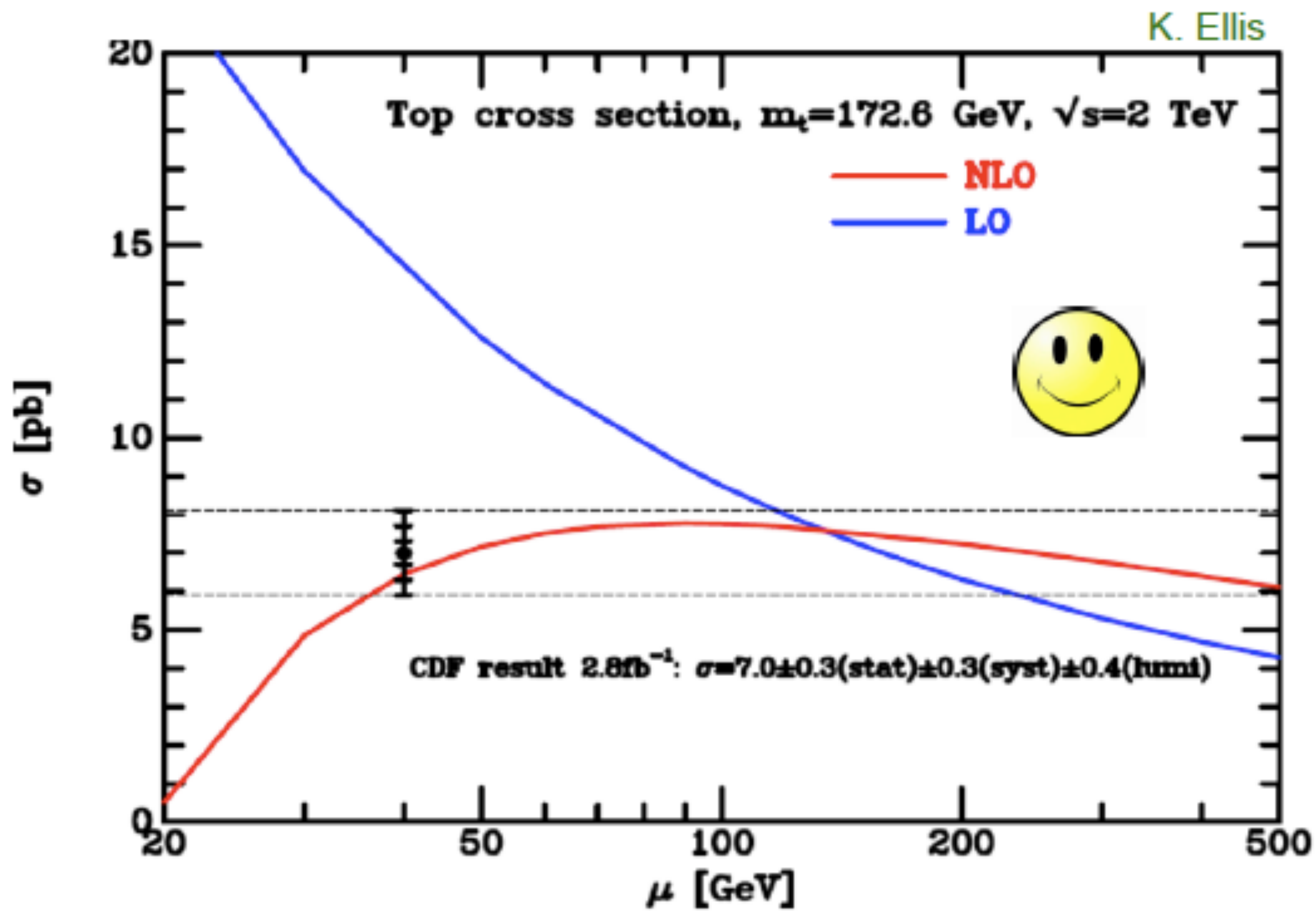
2. QCD & SM examples

I. QCD corrections
II. Jets
III. Hunting the Higgs at the LHC
IV. Top quark mass measurement

Motivation

- In order to have precise predictions working at LO might not be enough



[Stirling-Pascos 2011]

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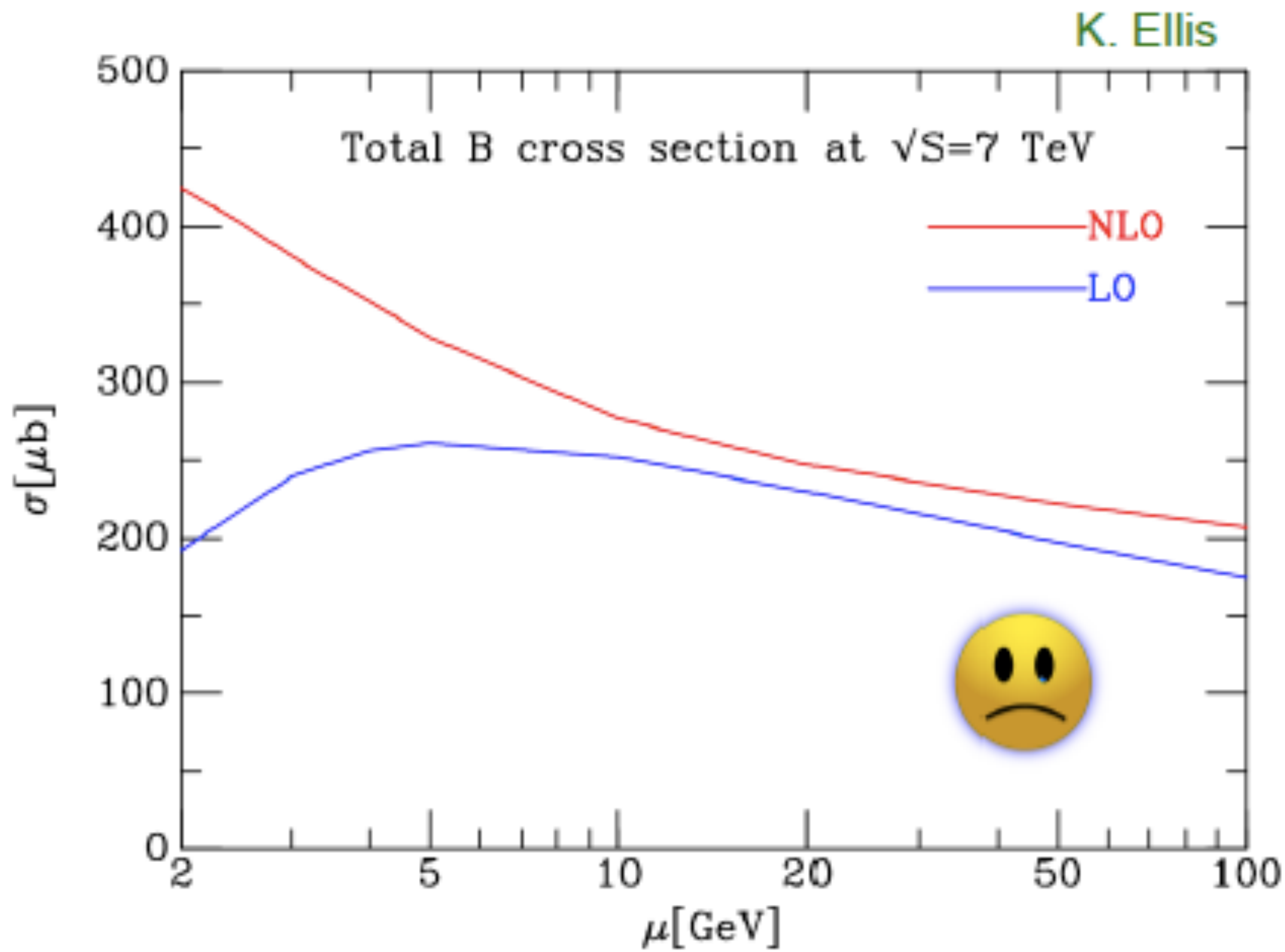
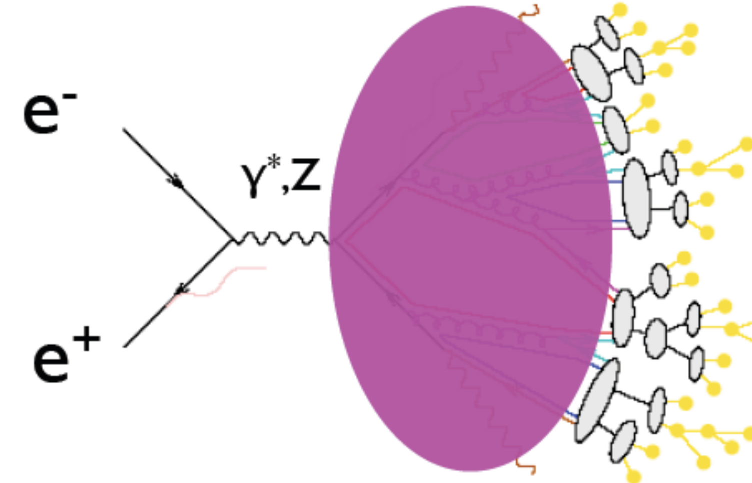


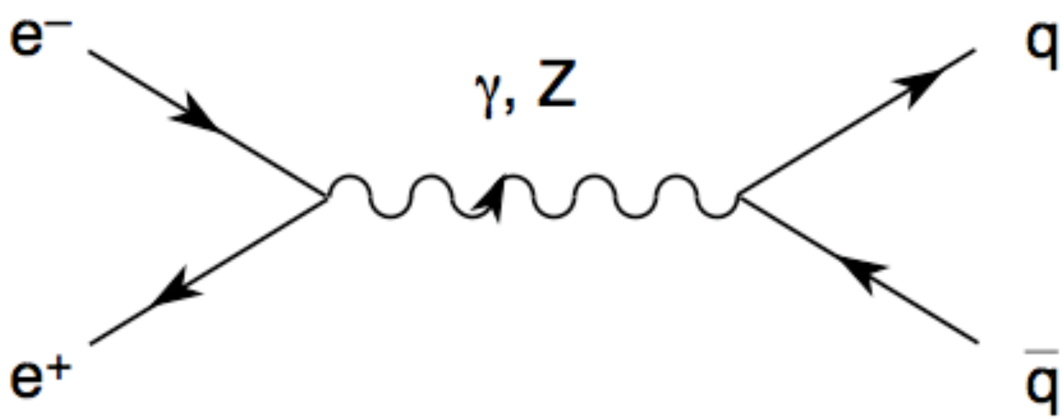
[Stirling-Pascos 2011]

I. QCD corrections



Total Cross Section

➡ Can we use pQCD despite confinement? "YES"



✻ The γ/Z virtuality is $Q = \sqrt{s}$

✻ Production occurs at a distance $\simeq \frac{1}{Q}$

✻ Q is large $\Longrightarrow$ pQCD applicable

➡ Hadronization changes quarks and gluons to hadrons.

➡ Hadronization takes place at a scale $\frac{1}{\Lambda}$.

➡ The change in the outgoing state occurs too late to modify the probability of the event to happen!

➡ Details of the final state certainly are changed.

Lowest Order Result (α_s^0)

- For simplicity, we neglect the Z contribution (i.e. $\sqrt{s} << M_Z$)

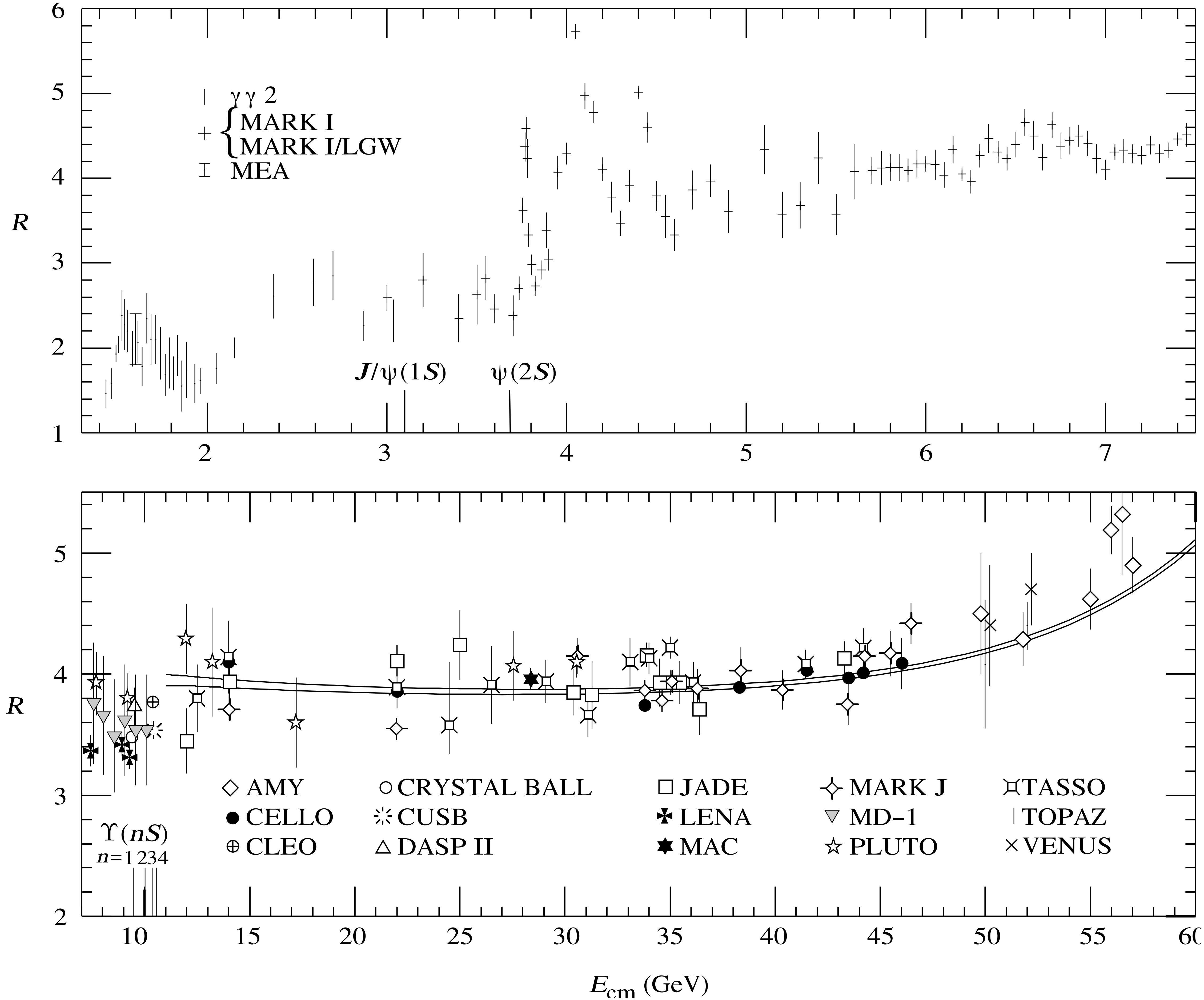
$$\frac{d\sigma_0}{d\cos\theta} = \frac{\pi\alpha^2 Q_f^2}{2s} N_c \left(1 + \cos^2\theta\right) \quad \Longrightarrow \quad \sigma_0 = \frac{4\pi\alpha^2}{3s} N_c\, Q_f^2$$

leading to

$$R_0 \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_q Q_q^2$$

- At the Z pole (i.e. neglecting γ), we have

$$R_0 = N_c \frac{\sum_q \left(A_q^2 + V_q^2\right)}{A_\mu^2 + V_\mu^2}$$

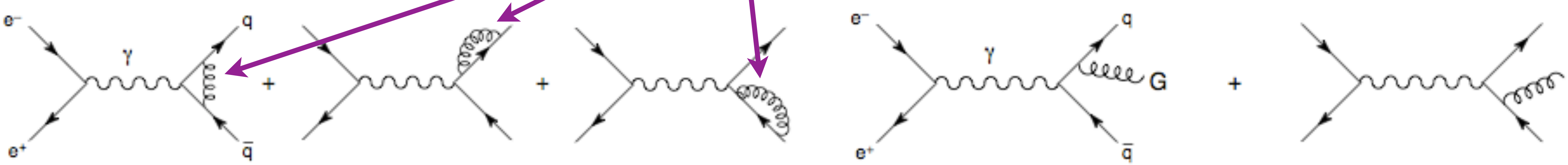


R
γγ 2
MARK I
MARK I/LGW
MEA
J/ψ(1S)
ψ(2S)
AMY
CELLO
CLEO
CRYSTAL BALL
CUSB
DASP II
JADE
LENA
MAC
MARK J
MD−1
PLUTO
TASSO
TOPAZ
VENUS
ϒ(nS)
n=1234
E_cm (GeV)

Next Order Correction (α_s^1)

$$\int \frac{d^4k}{k^4}$$

- We should evaluate



- Writing $\mathcal{M}^P = \mathcal{M}_0^P + \mathcal{M}_1^P$, the α_s contribution has the form

$$\int d\Phi_2 \left[2\,\mathrm{Re} \left(\mathcal{M}_0^{2\to 2} \right)^\dagger \mathcal{M}_1^{2\to 2} \right] + \int d\Phi_3 \, |\mathcal{M}_0^{2\to 3}|^2$$

- After adding all contributions the UV divergences cancel out (Ward identity). The same happens for the IR ones!

$$R = R_0 \left(1 + \frac{\alpha_s(\mu)}{\pi} \right) \longrightarrow R_0 \left(1 + \frac{\alpha_s(\sqrt{s})}{\pi} \right)$$

➯ Unlike UV divergences, there is no renormalization for the IR ones. They indicate sensitivity to long range physics like masses, hadronization process, etc.

➯ The singularities are not physical; they indicate the breakdown of the perturbative approach. Quarks and gluons are never on mass–shell–particles and we can not ignore the effects of confinement at a scale $\simeq 1$ GeV.

General form of the IR divergences for $p_g \to 0$

$$\sigma^{q\bar{q}g} = \frac{2\alpha_s}{3\pi}\sigma_{q\bar{q}} \int d\cos\theta_{qg} \frac{dE_g}{E_g} \frac{4}{(1-\cos\theta_{qg})(1+\cos\theta_{qg})}$$

NLO in hadron colliders

- The parton model expression for cross sections is

$$\sigma = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_1\, dx_2 \qquad \left\{ f_i(x_1, Q_F^2) f_j(x_2, Q_F^2) \;+\; i \leftrightarrow j \right\} \otimes$$

$$\hat{\sigma}_{ij}(\alpha_s(Q_R^2), Q_R^2, Q_F^2; x_1 x_2 s)$$

- Expanding the pdf's and $\hat{\sigma}$ ($X = X^{(0)} + X^{(1)} + \cdots$) the lowest order term is

$$\sigma = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_1\, dx_2 \left\{ f_i^{(0)}(x_1) f_j^{(0)}(x_2) \;+\; i \leftrightarrow j \right\} \otimes \hat{\sigma}_{ij}^{(0)}(x_1 x_2 s)$$

➪ The NLO contribution is obtained through

$$[f_i^{(1)} f_j^{(0)} + f_i^{(0)} f_j^{(1)} + i \leftrightarrow j] \times \hat{\sigma}^{(0)} \oplus [f_i^{(0)} f_j^{(0)} + i \leftrightarrow j] \times \hat{\sigma}^{(1)}$$

➪ The red term contains collinear divergences that are canceled by the divergences in the blue term.

• Scales:

- The evaluation of $\hat{\sigma}$ contains a UV divergence => renormalization => remnant of the process is the renormalization scale μ_R
- Full calculation should not depend on μ_R => we can estimate the higher order corrections by the μ_R dependence
- At each order, the subprocess cross section and the PDF's have a residual factorization scale dependence on μ_F
- The residual scale dependence should improve with higher order calculations

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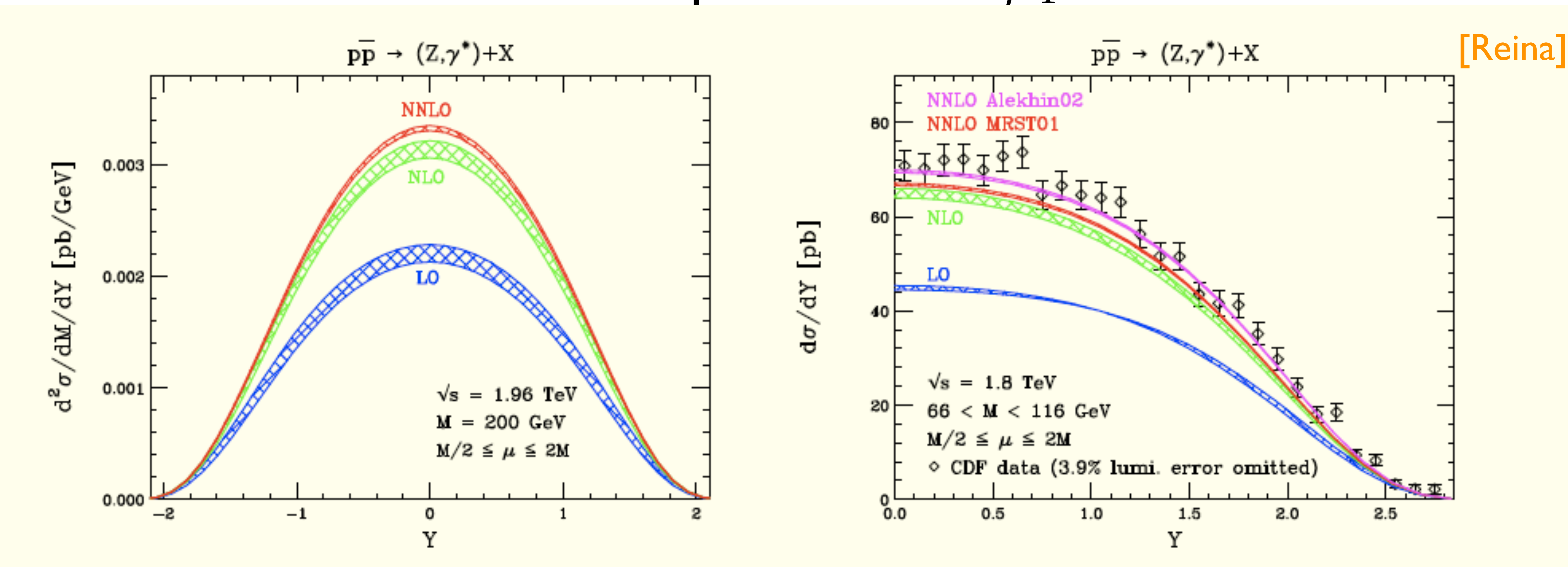
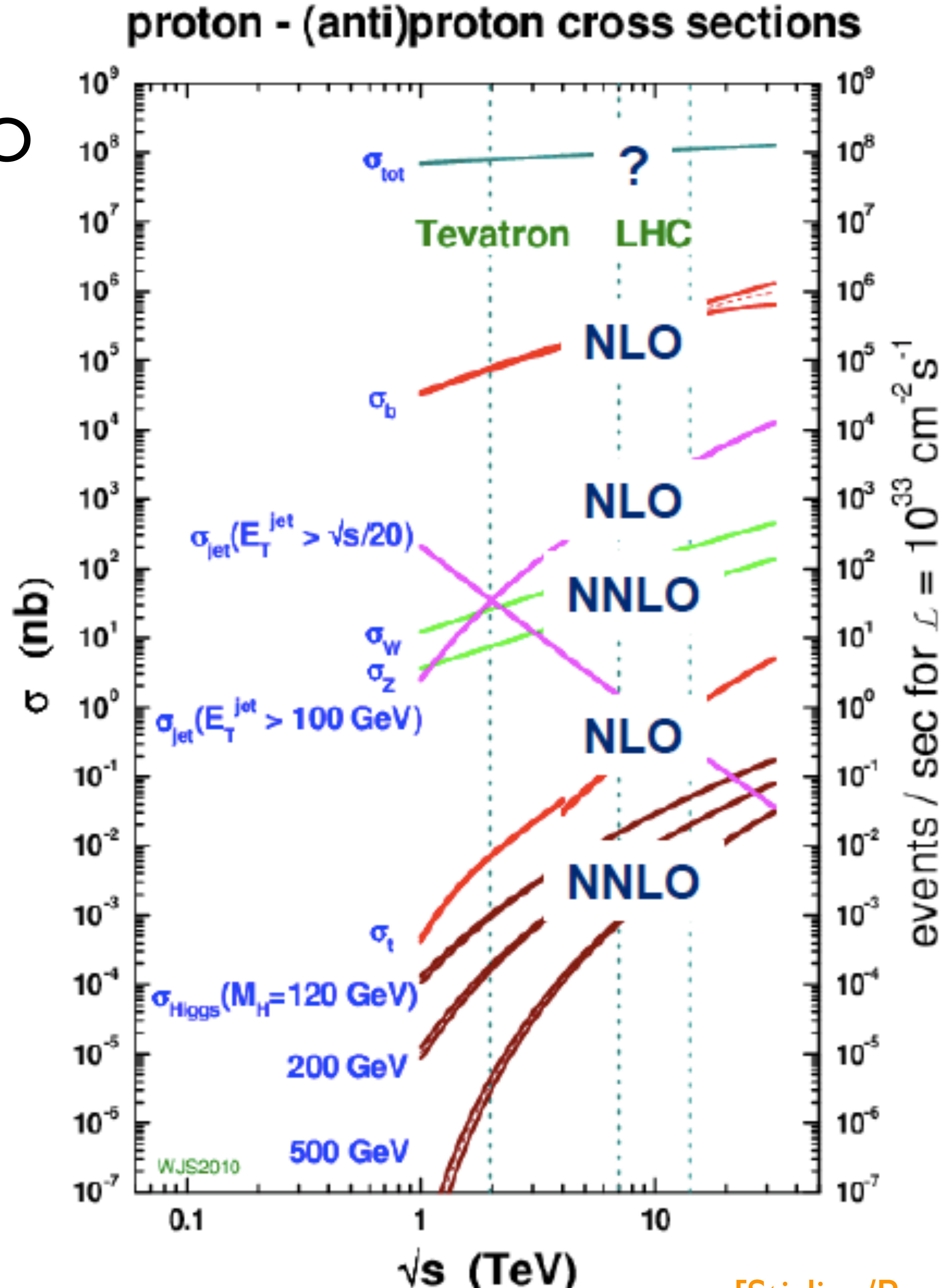


(C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello, PRL 91 (2003) 182002)

- many available
- automatic NLO

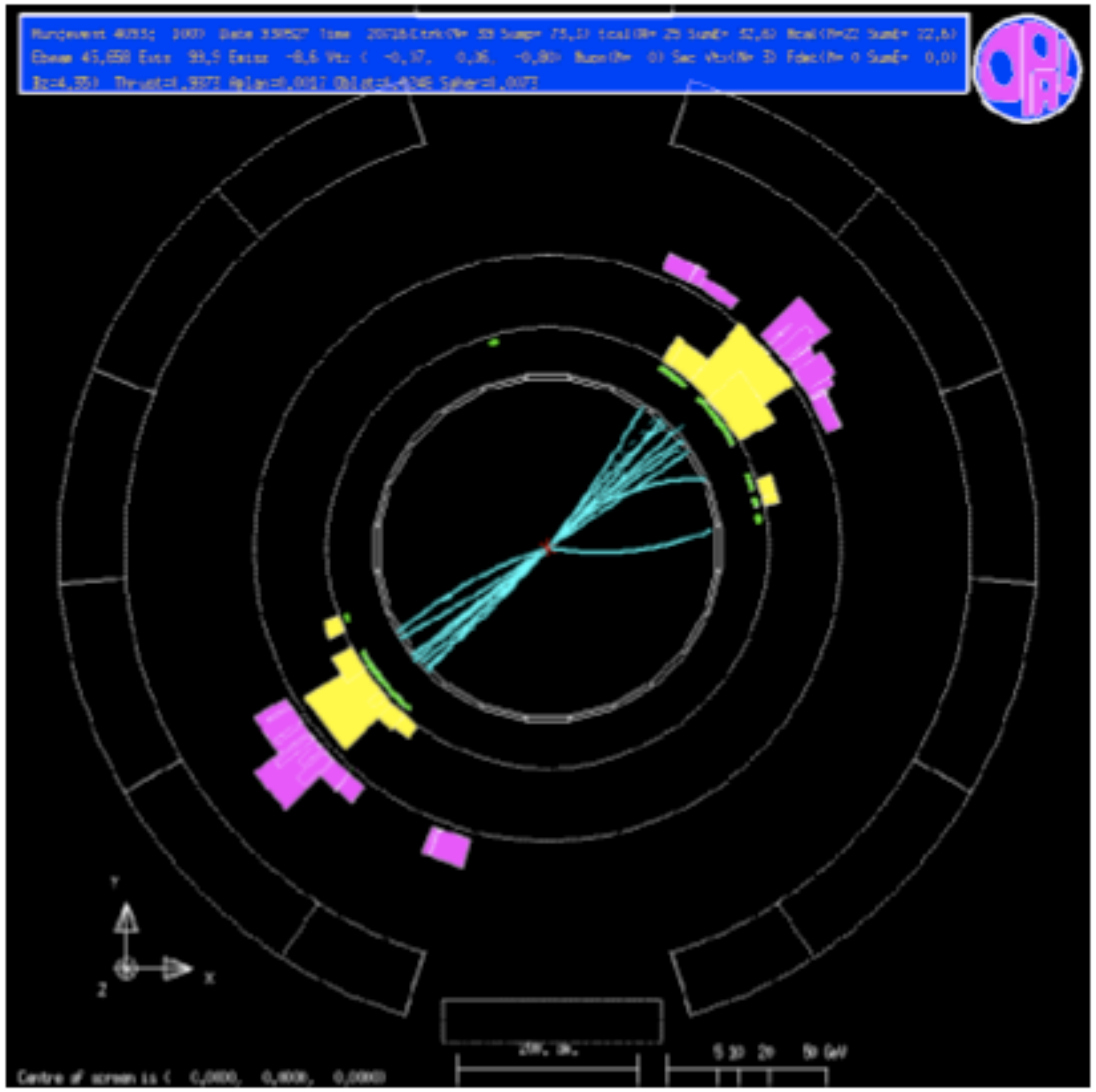


[Stirling/Pascos]

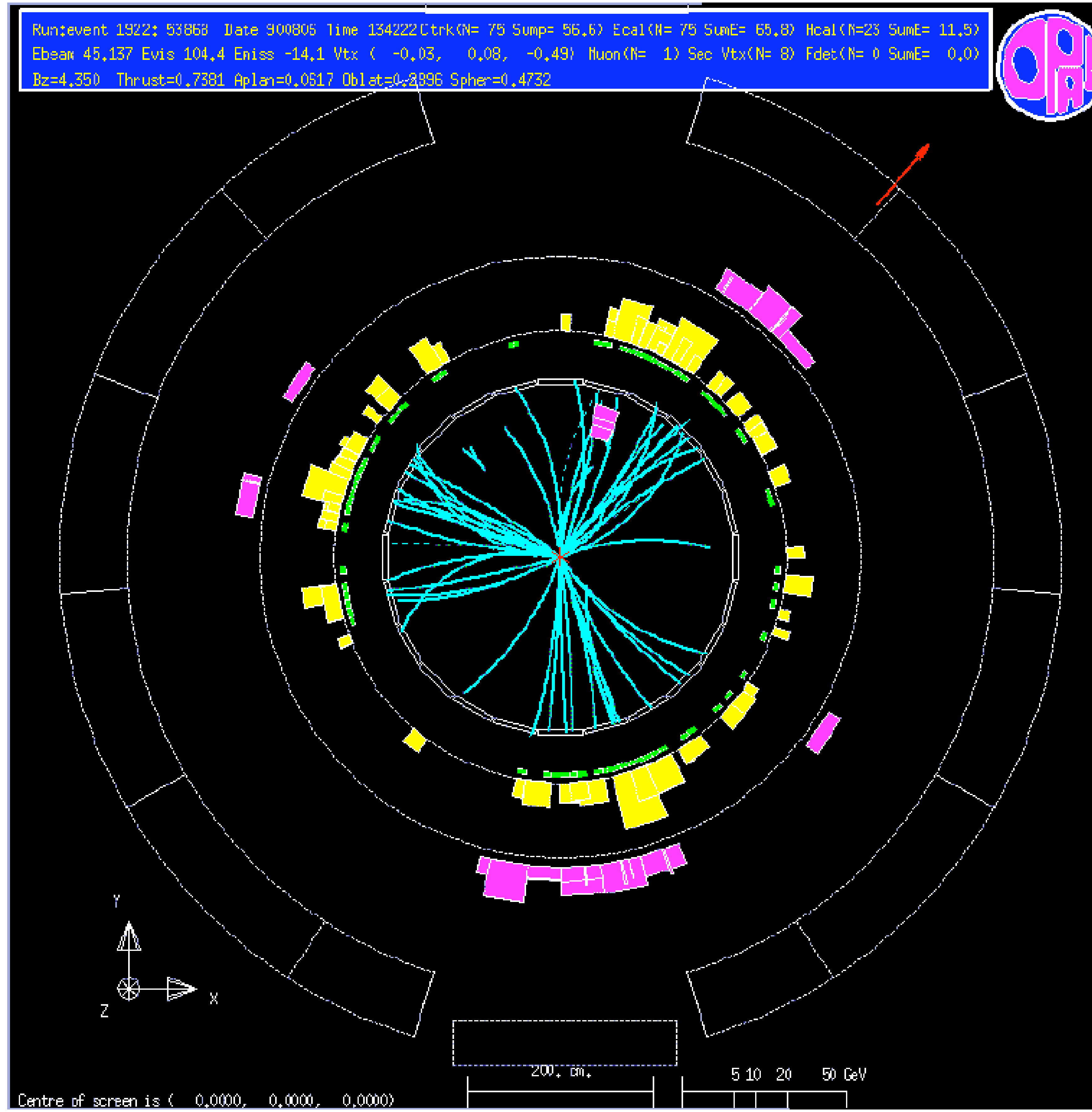
II. Jets

➡ Can we obtain more information on the hadron production besides the total cross section?

➡ We expect that soft process don't change completely the high energy features $\Longrightarrow$ a spray of hadrons follows the direction of the original quarks and gluons.

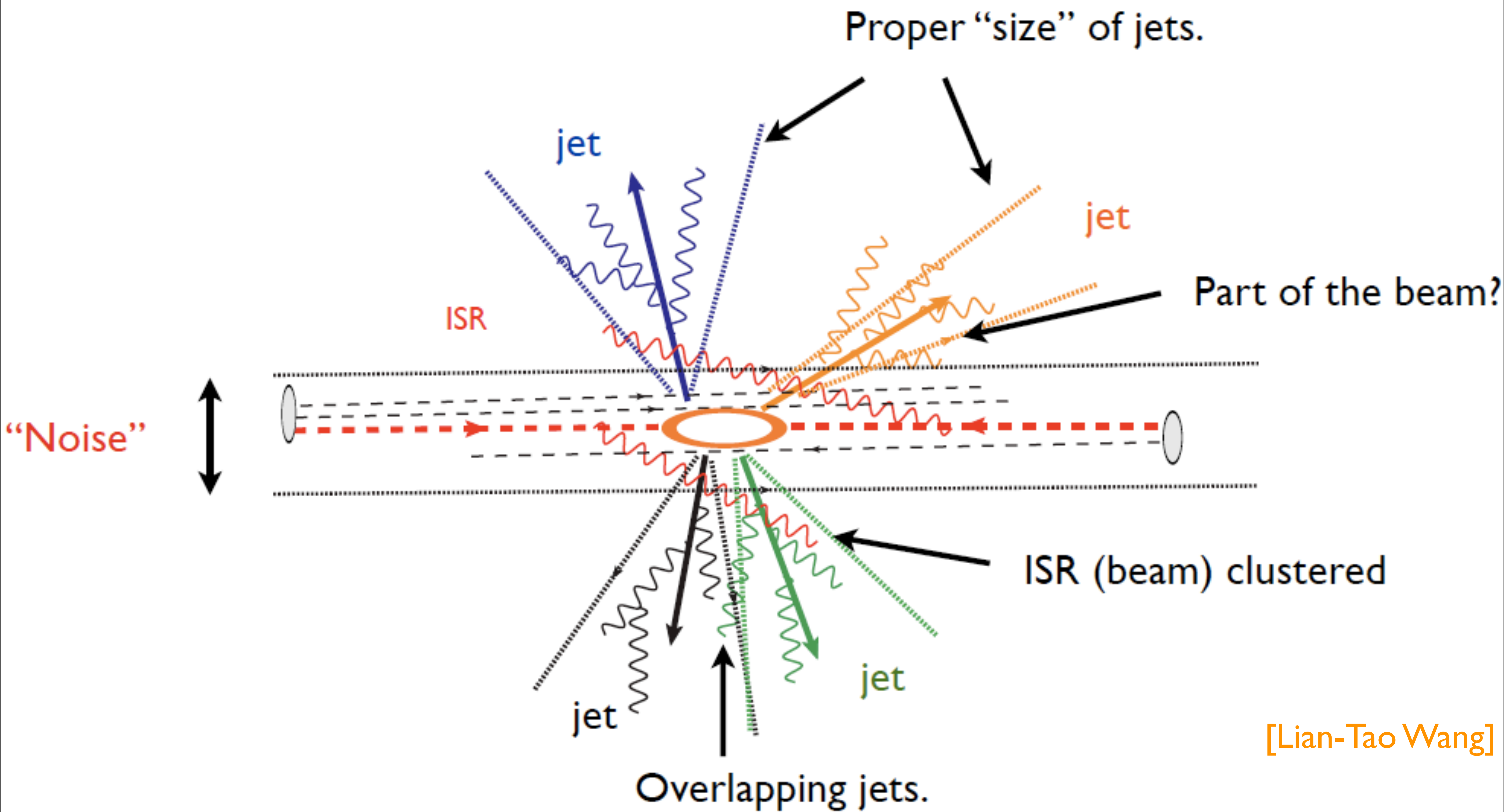


Three jet event:



- why not 4?
- Which particles belong to a jet?
- how to get $p_{parton} \simeq p_{jet}$?

Not an easy task:



[Lian-Tao Wang]

Criteria for a good jet recipe: [Snowmass]

1. Simple to implement in an experimental analysis
2. Simple to implement in a theoretical calculation
3. Defined at any order of perturbation theory
4. Yields finite cross sections at any order of PT
5. Yields a cross section rather insensitive to hadronization

A few jet algorithms

- Three popular jet algorithms are kT, anti-kT, and Cambridge/Aachen
- The distance and rule to join objets is

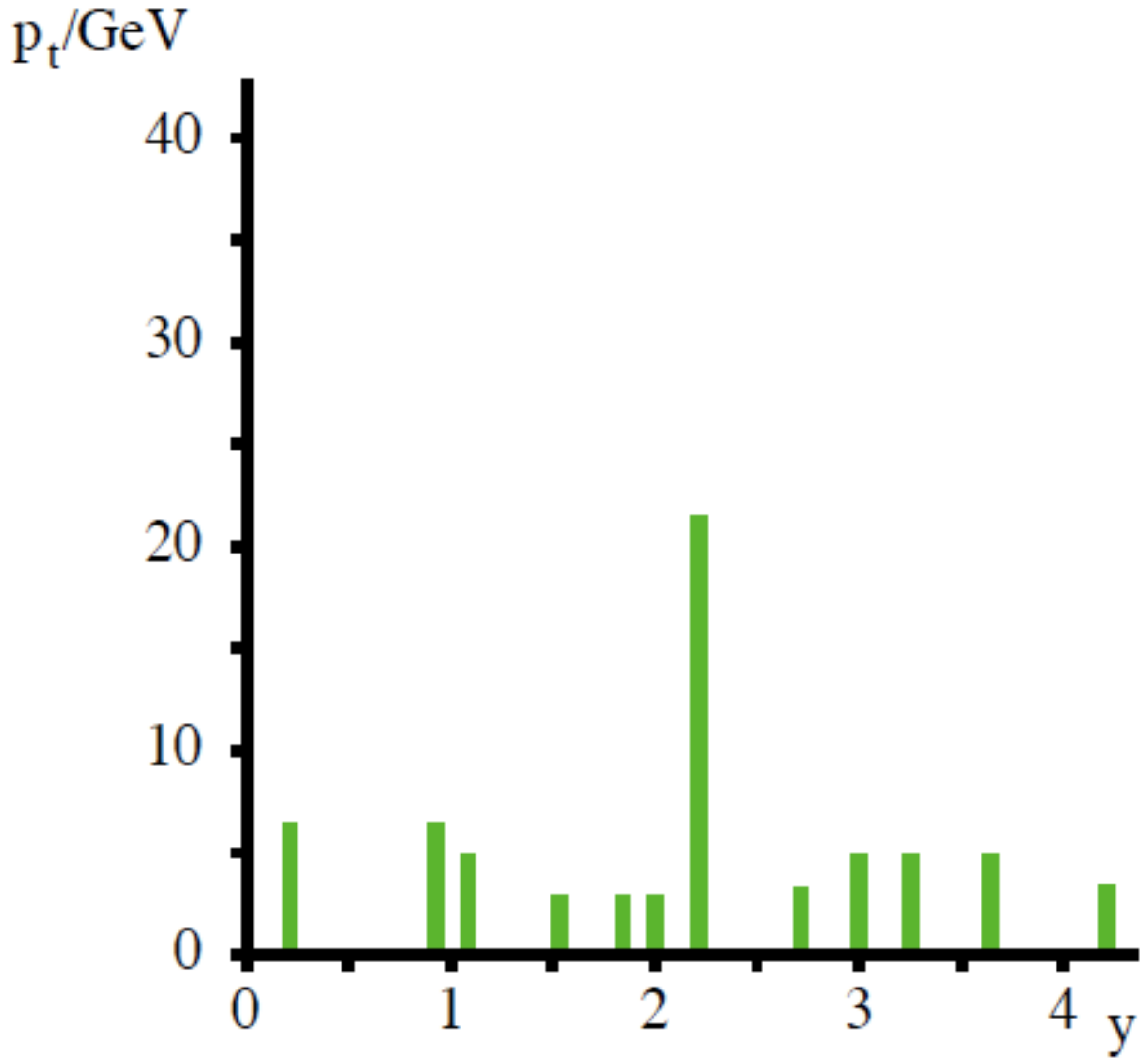
$$\mathbf{d_{ij}} = \min[\mathbf{p_{Ti}^{2\alpha}}, \mathbf{p_{Ti}^{2\alpha}}] \left(\frac{\mathbf{\Delta R_{ij}}}{\mathbf{R}}\right)^{\mathbf{2}} \quad \text{and} \quad \mathbf{d_{iB}} = \mathbf{p_{Ti}^{2\alpha}}$$

with $\mathbf{\Delta R_{ij}} = \sqrt{\mathbf{\Delta}\eta_{\mathbf{ij}}^{\mathbf{2}} + \mathbf{\Delta}\varphi_{\mathbf{ij}}^{\mathbf{2}}}$

repeatedly combine objets until $\mathbf{d_{iB}}$ is the smaller distance.
Then call it a jet, remove from the list and start again

- The choices are: kT ($\alpha = \mathbf{1}$); anti-kT ($\alpha = -\mathbf{1}$); C/A ($\alpha = \mathbf{0}$)

- Example with C/A algorithm [borrow from G. Salam] $R = 1$



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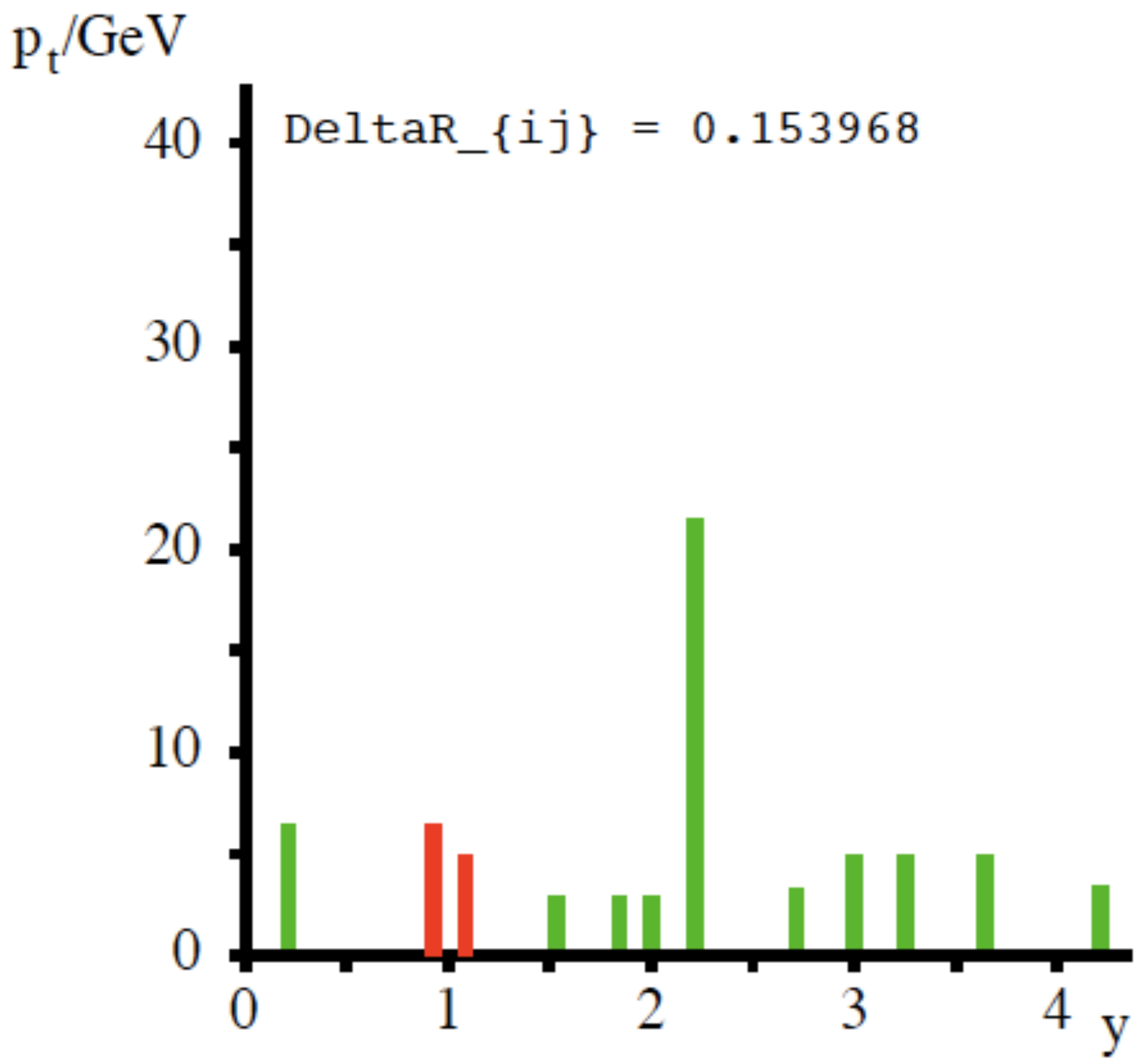

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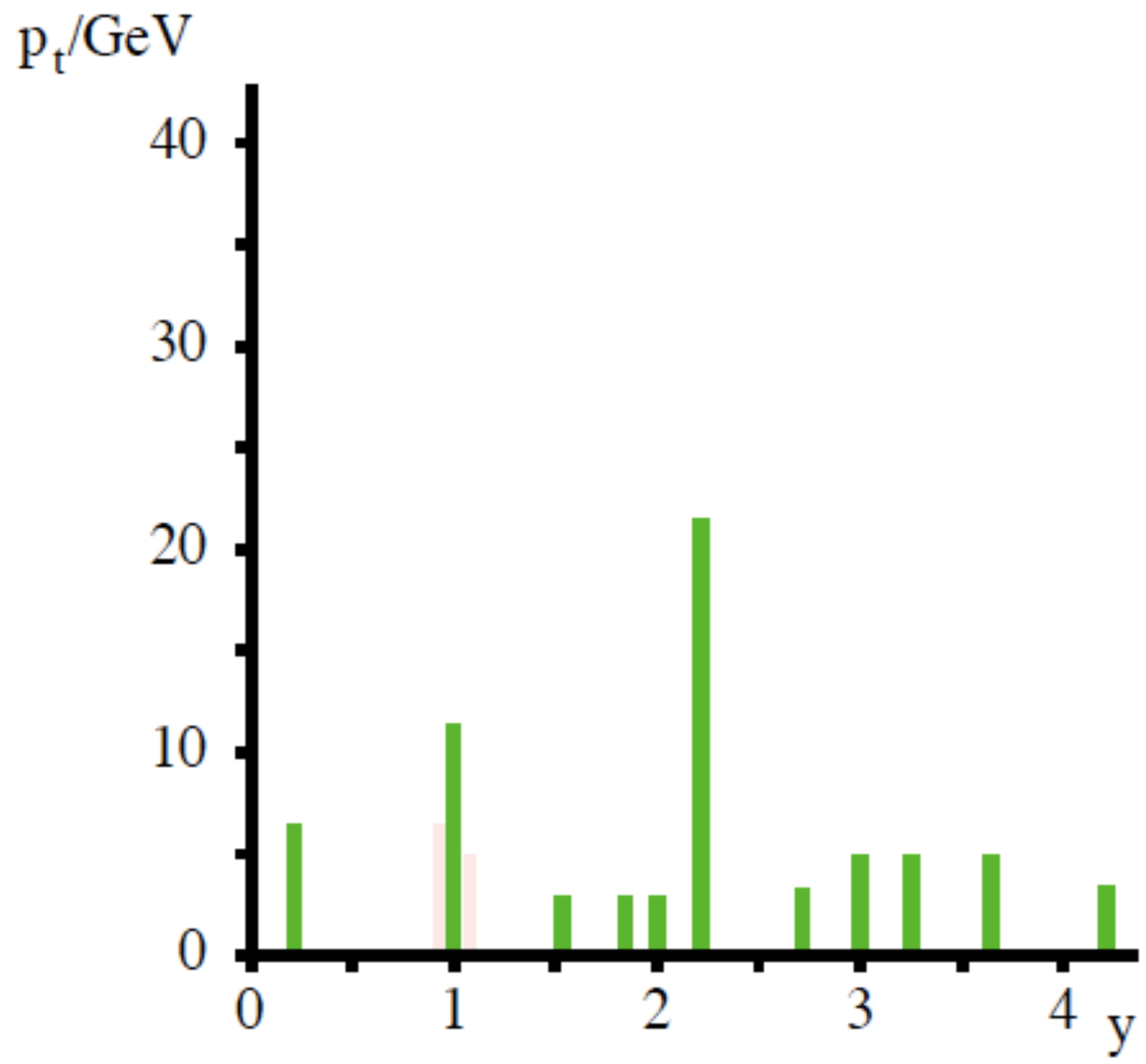

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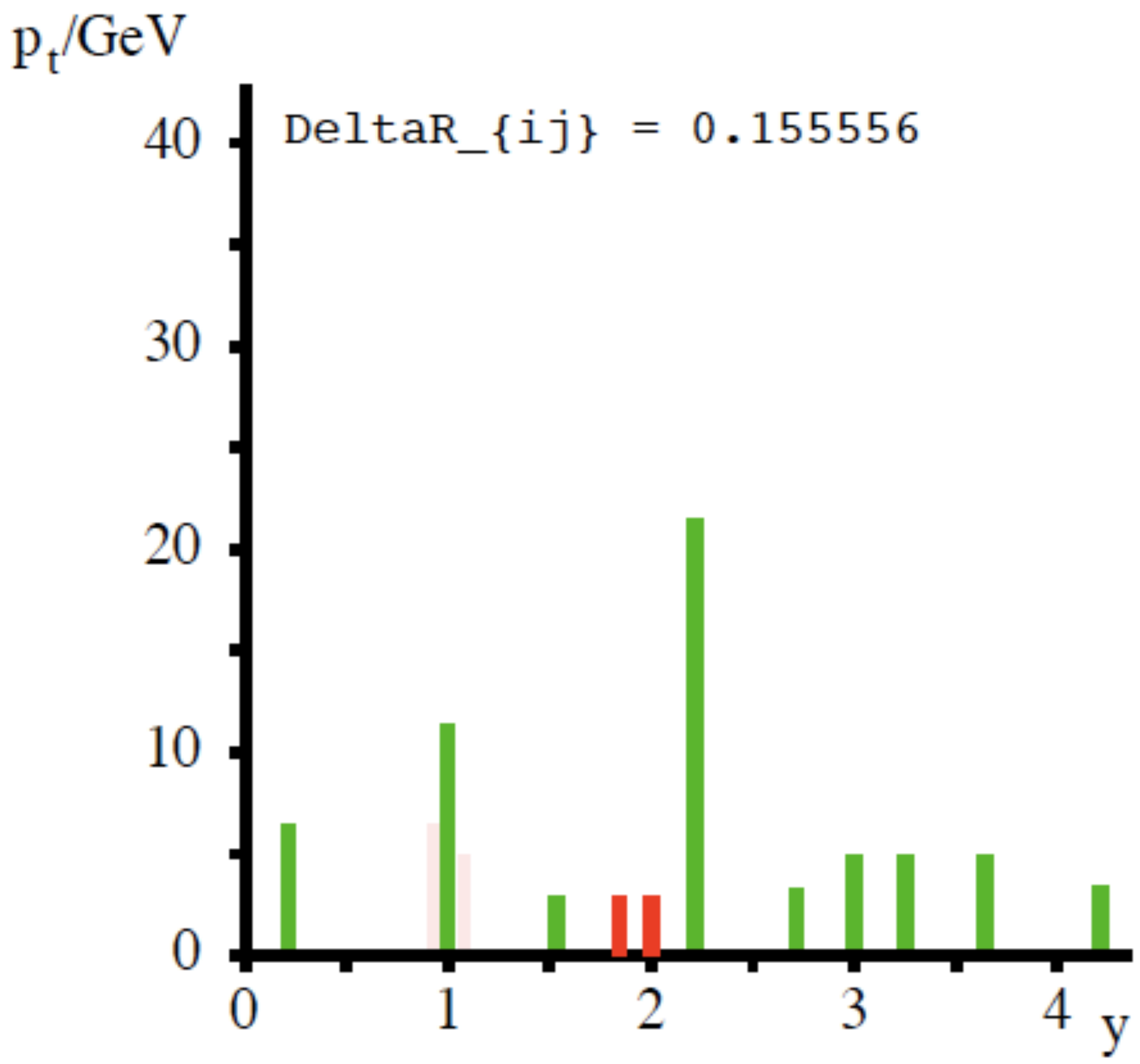

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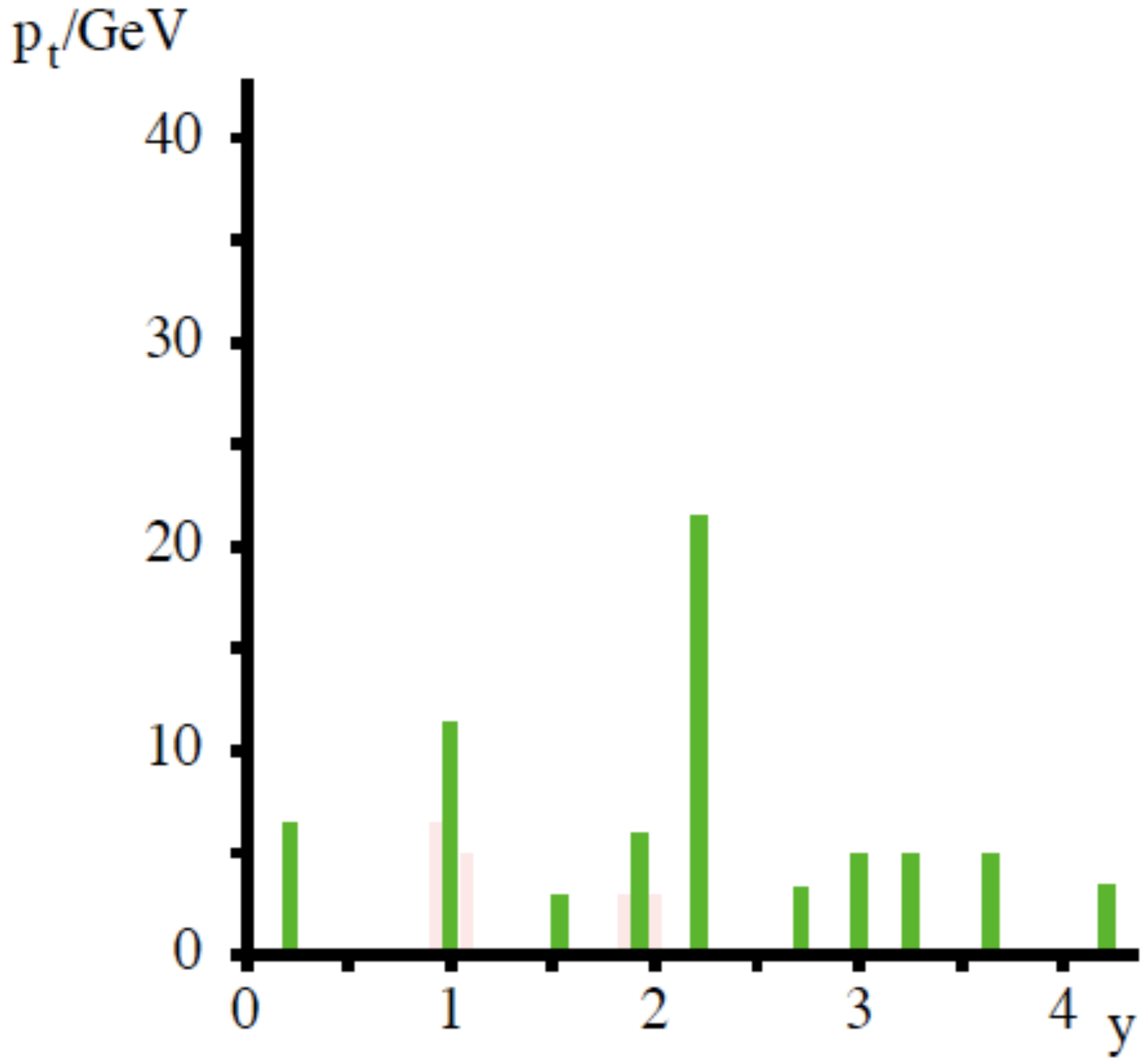

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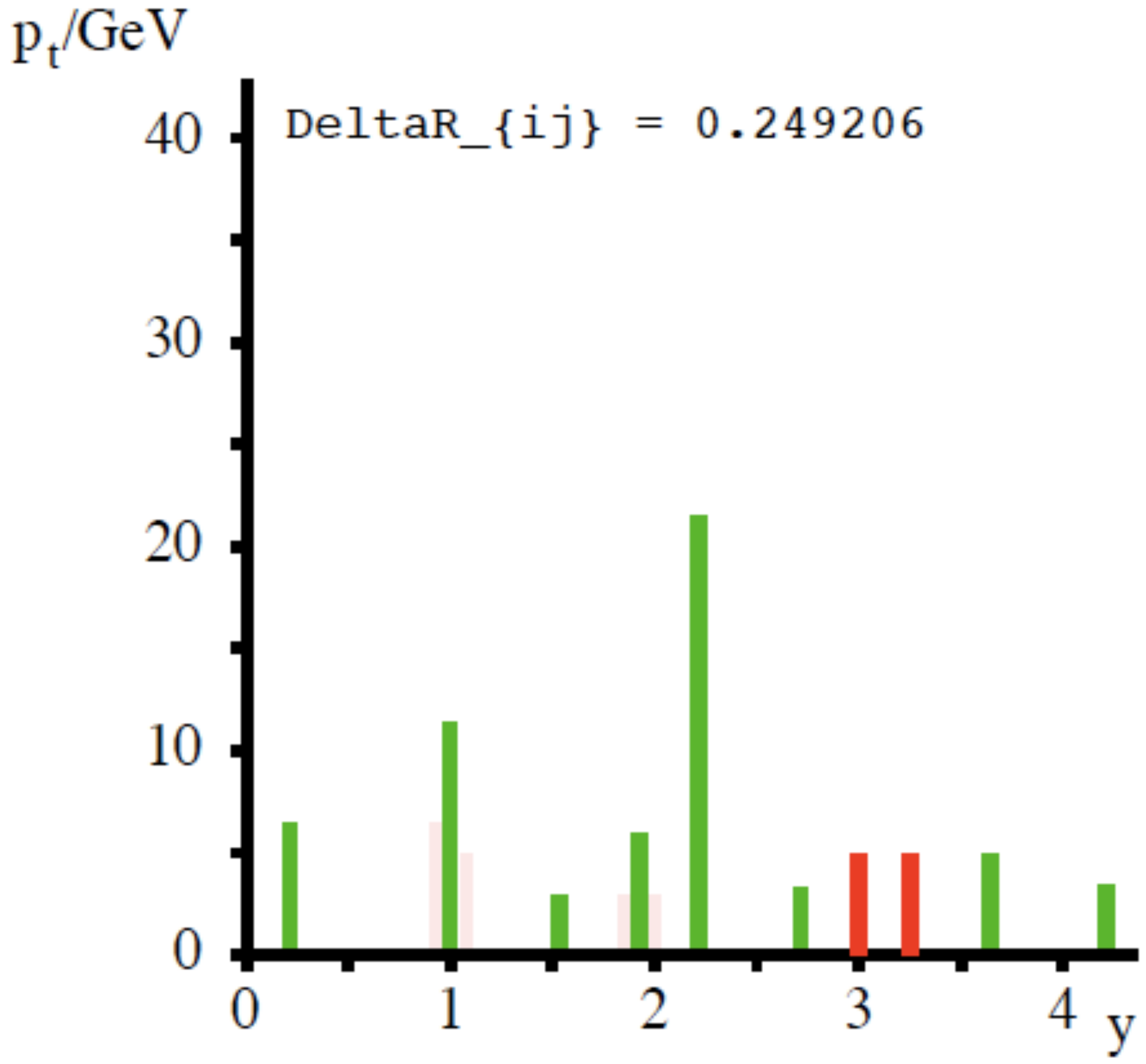

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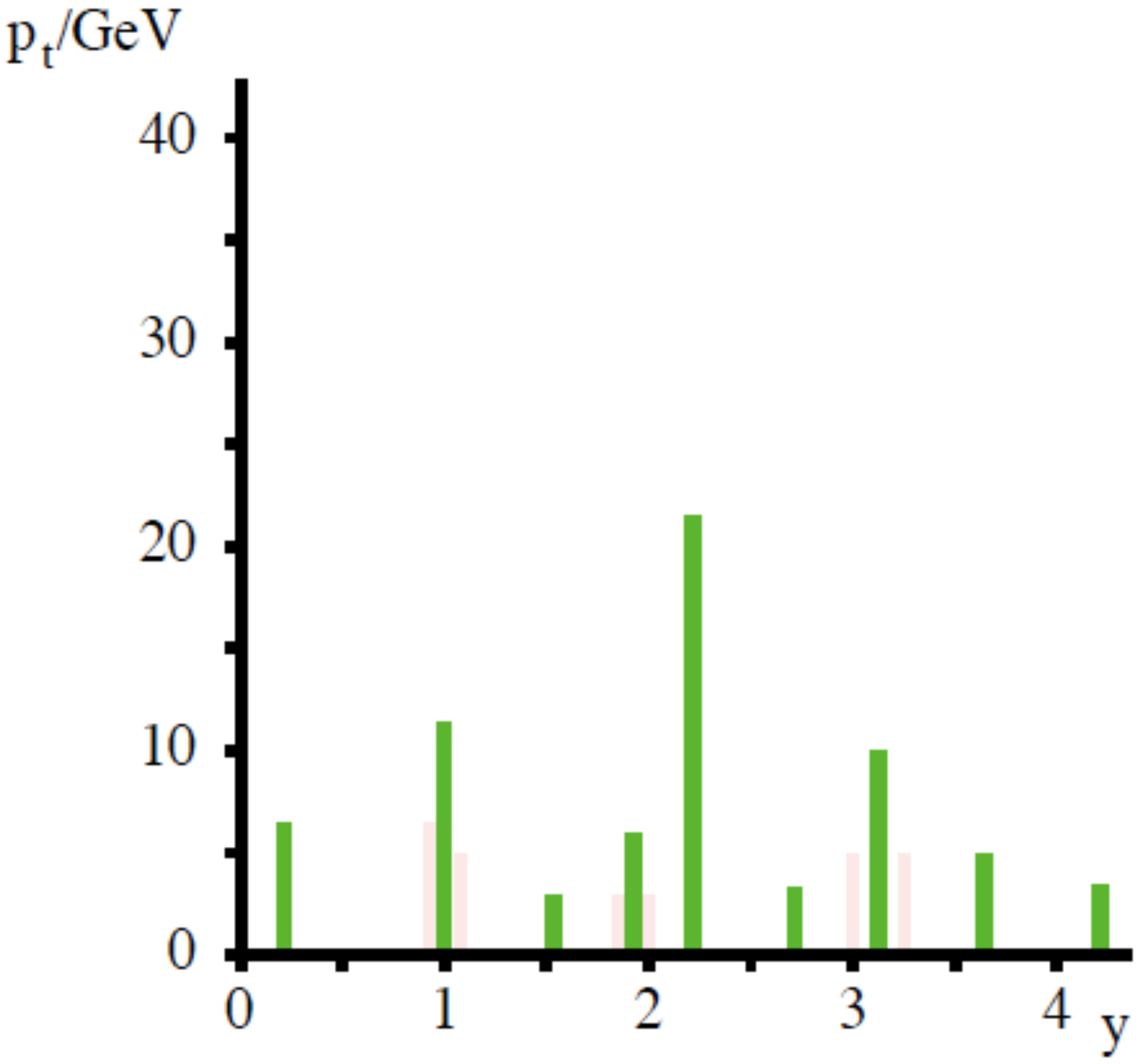

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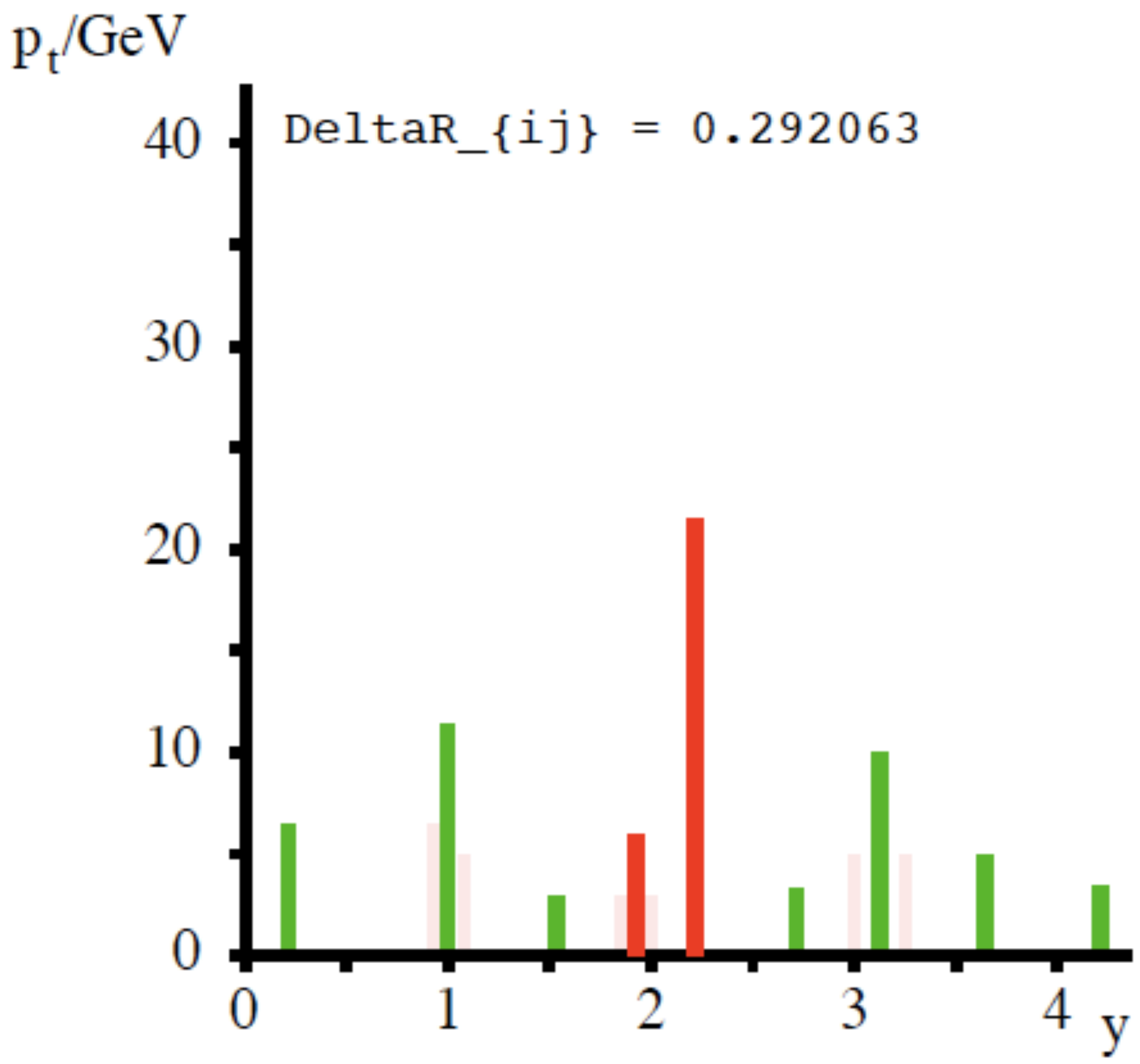

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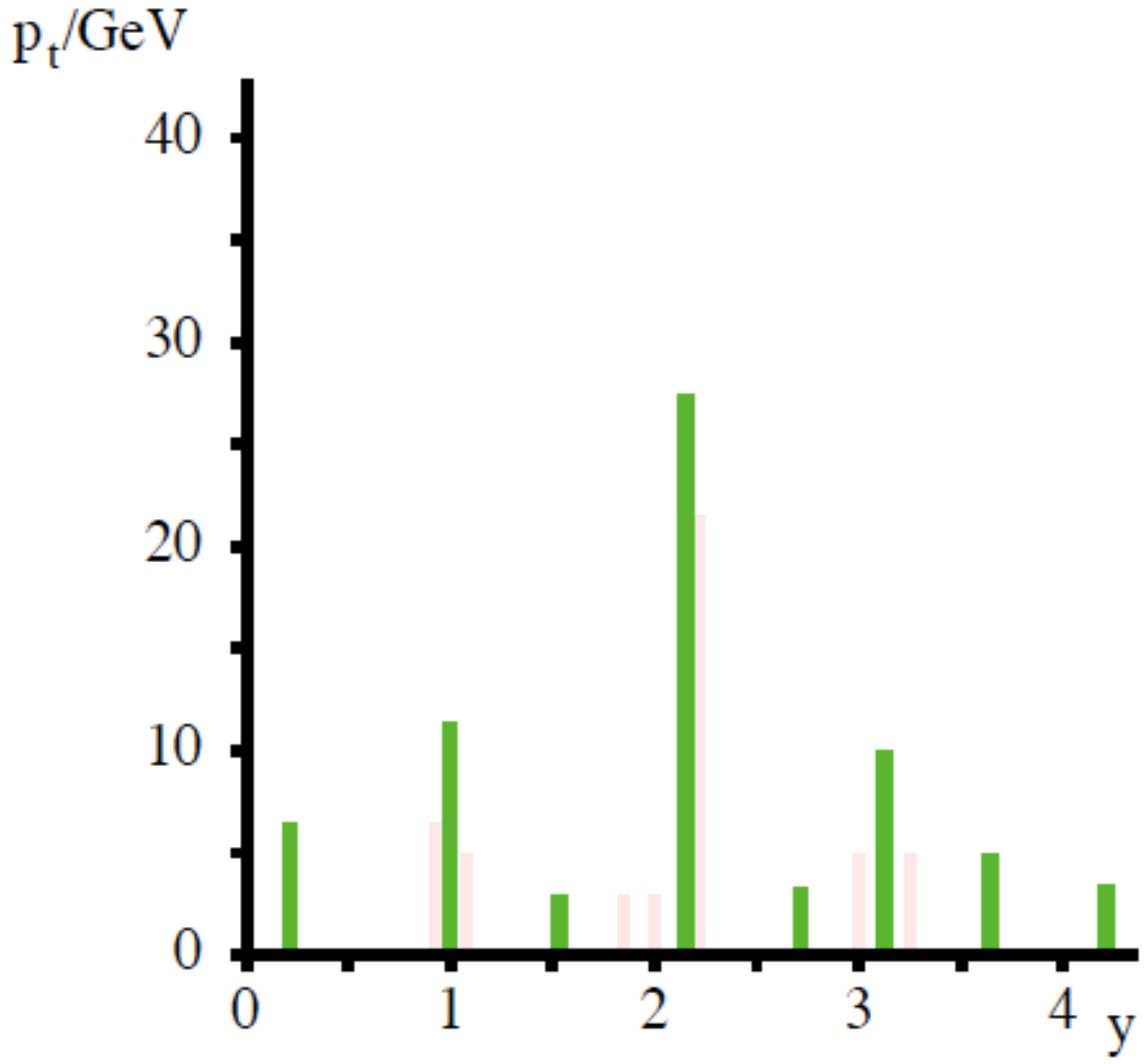

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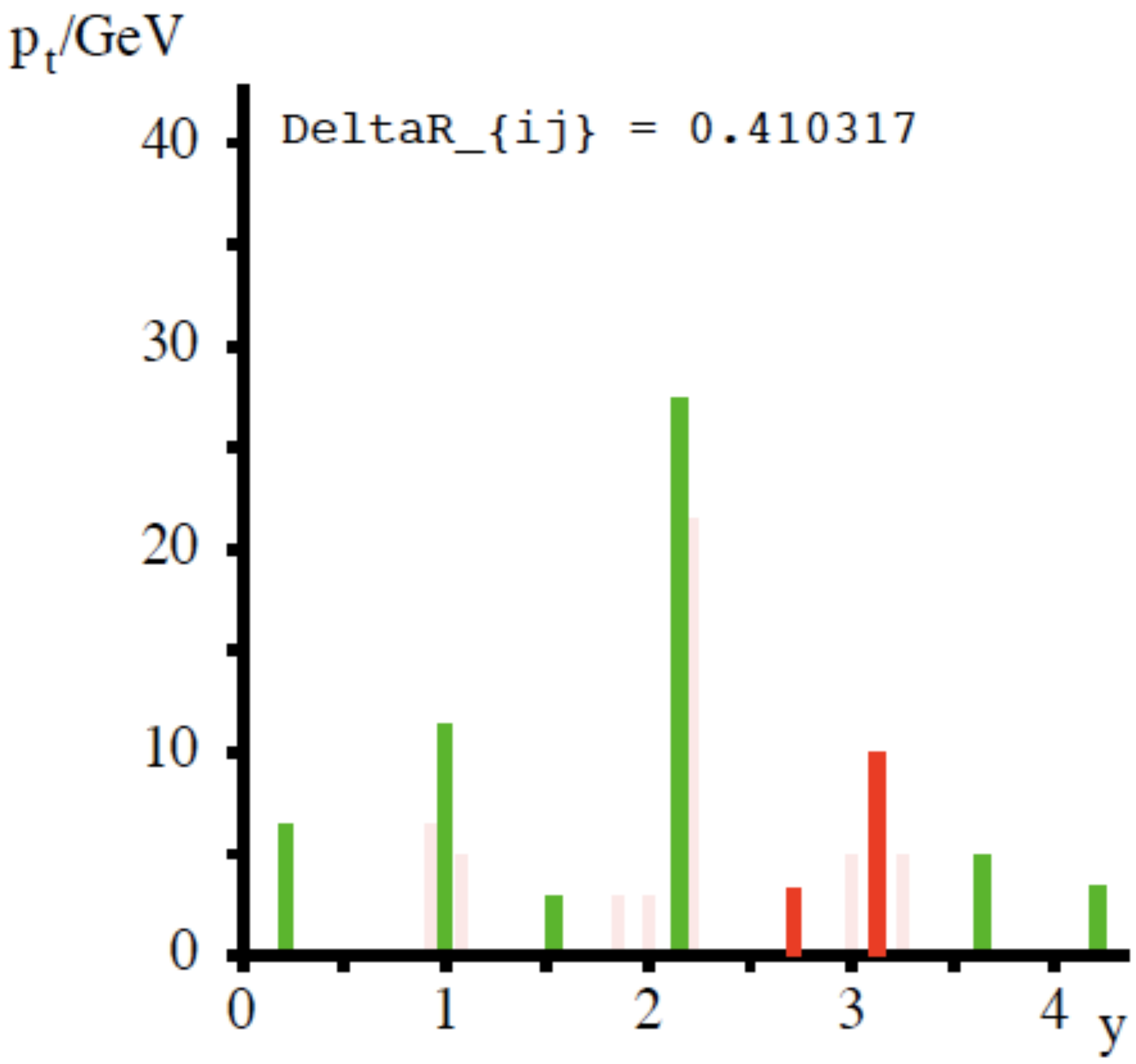

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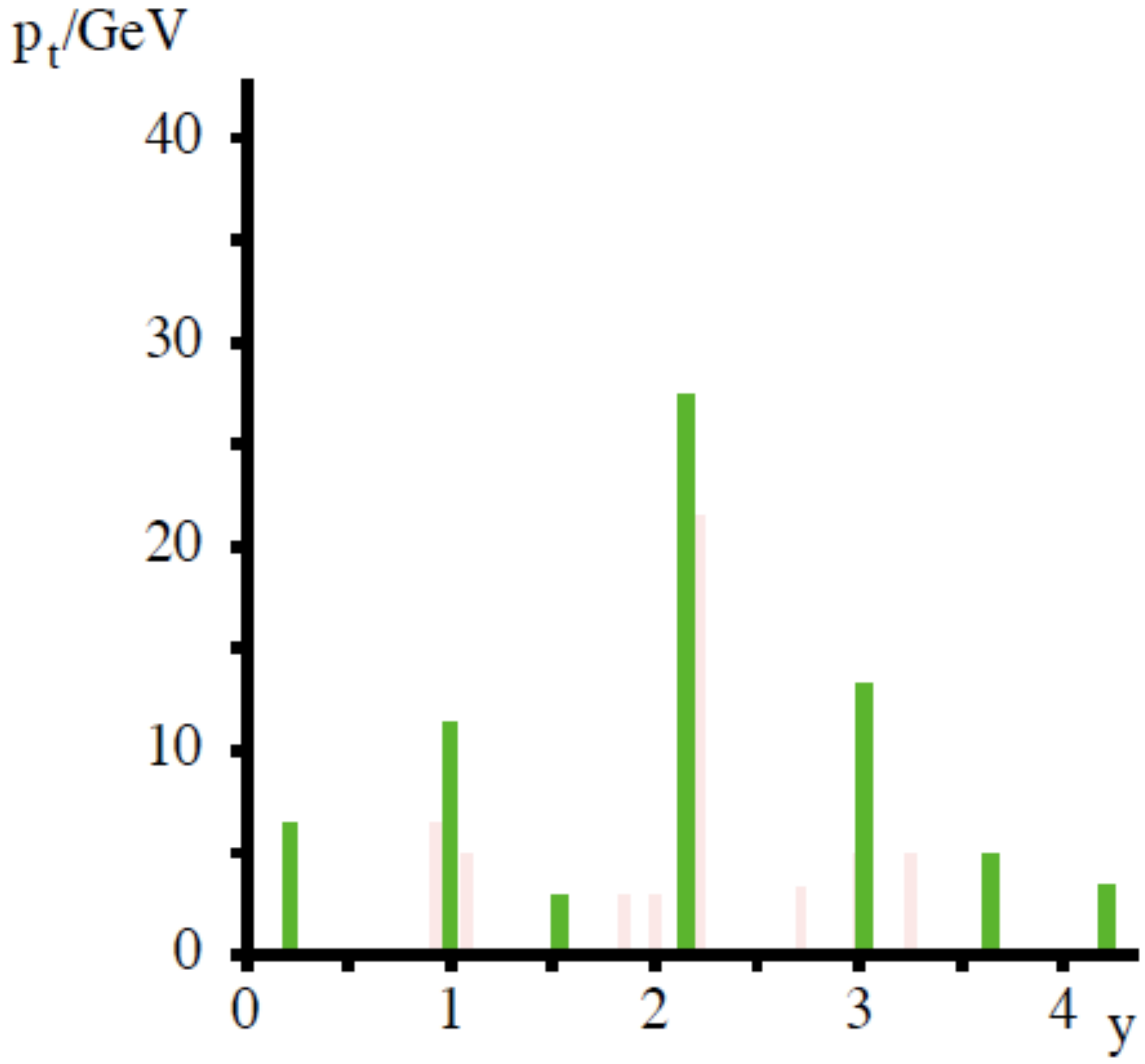

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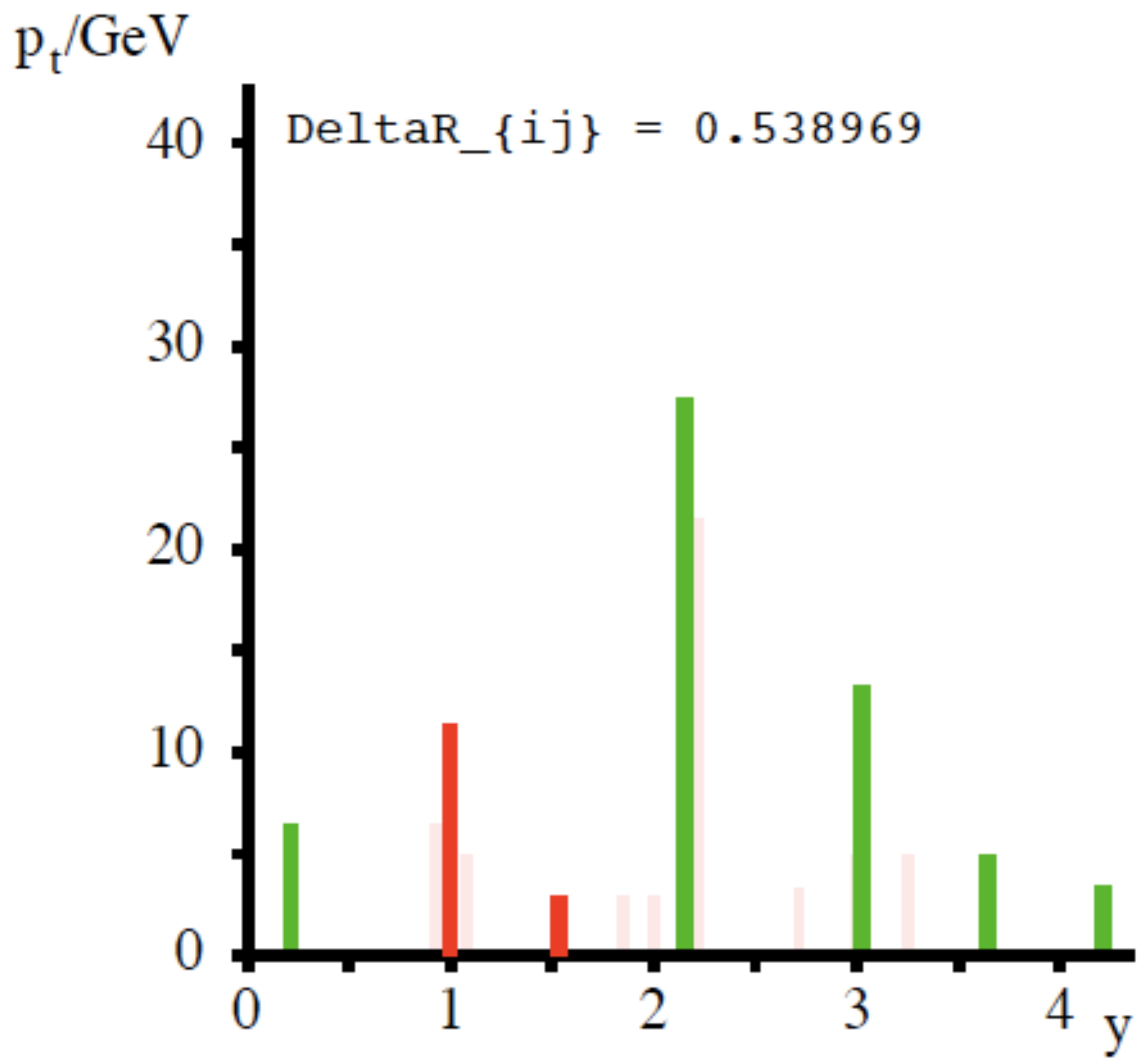

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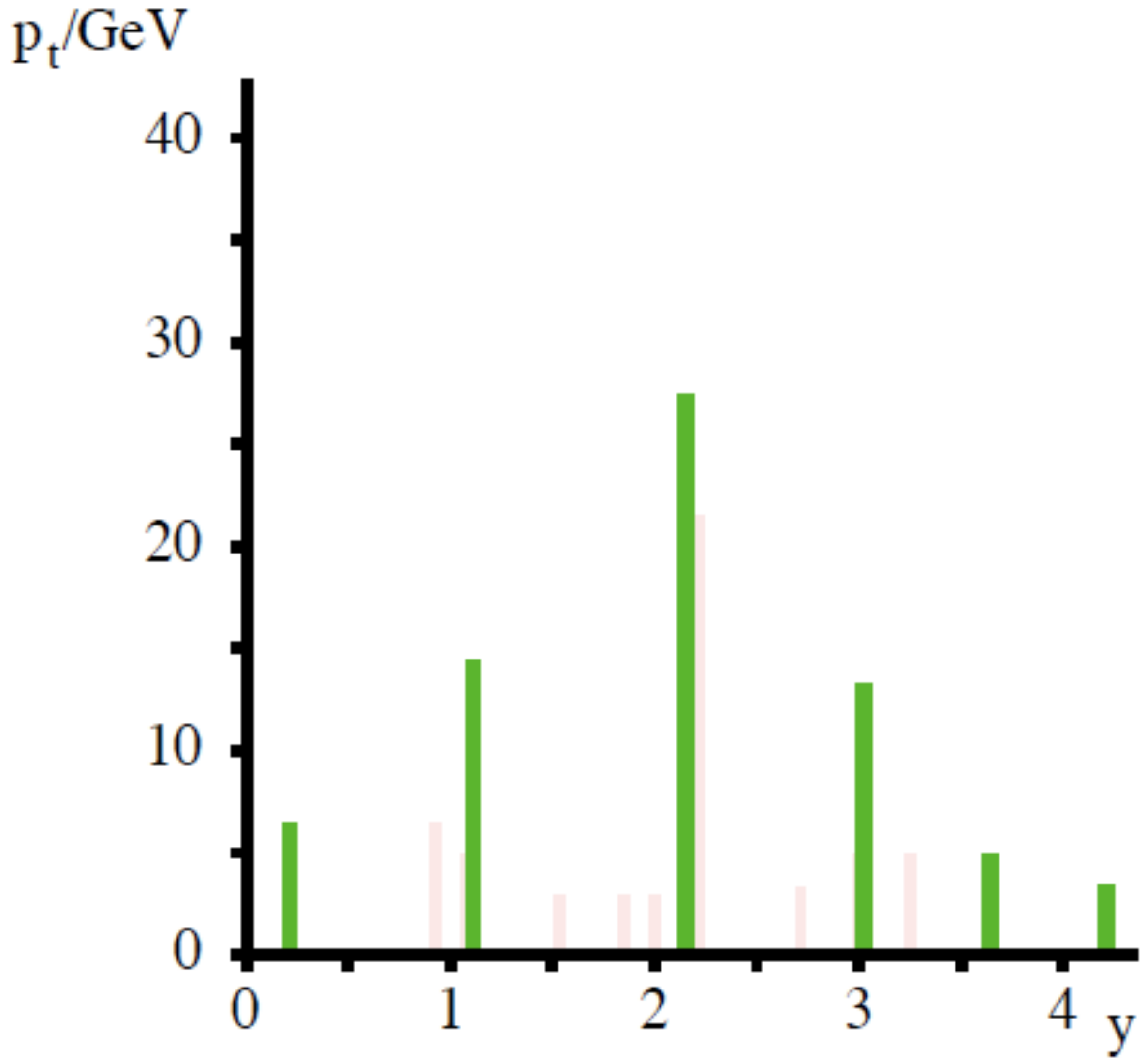

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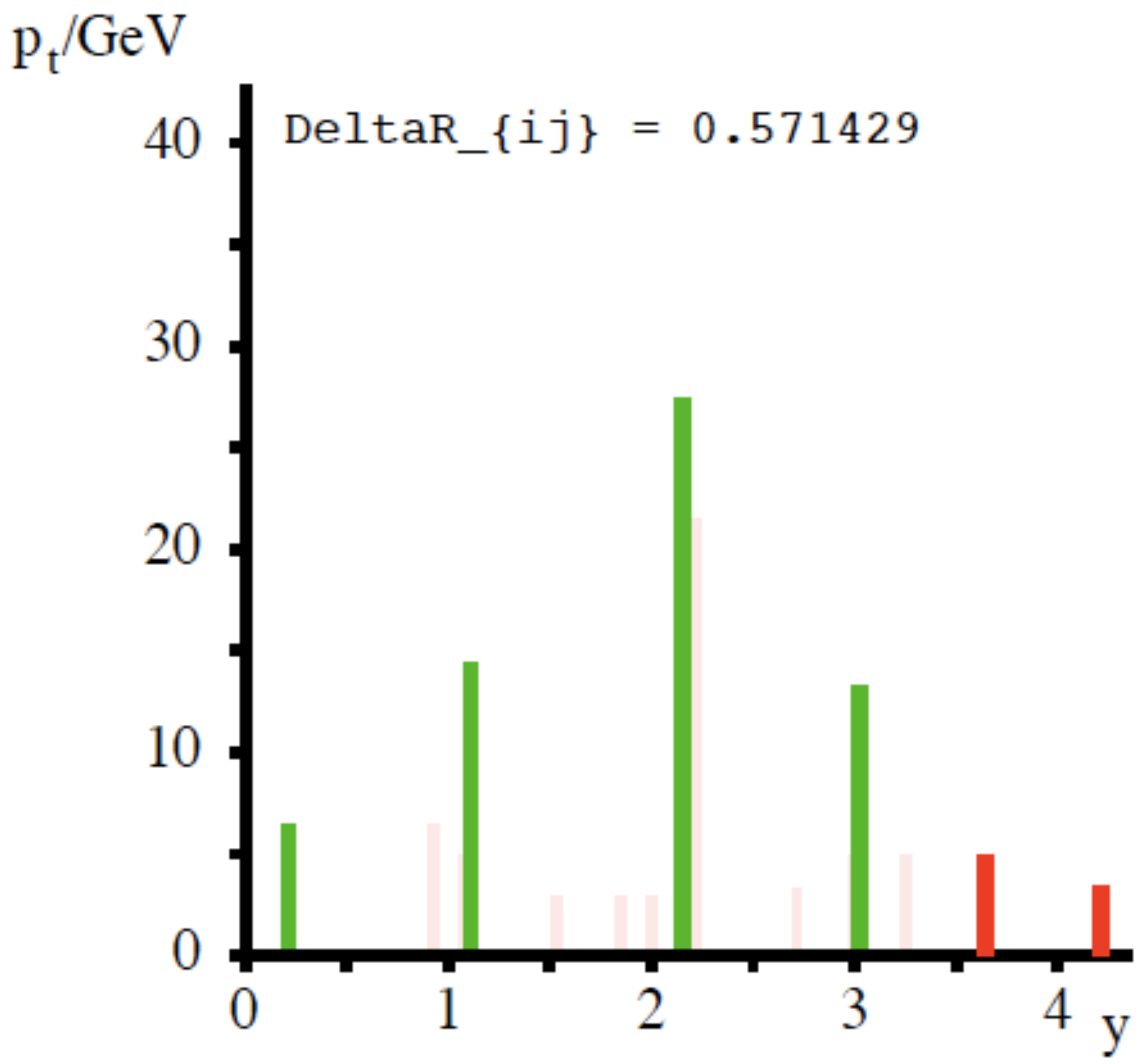

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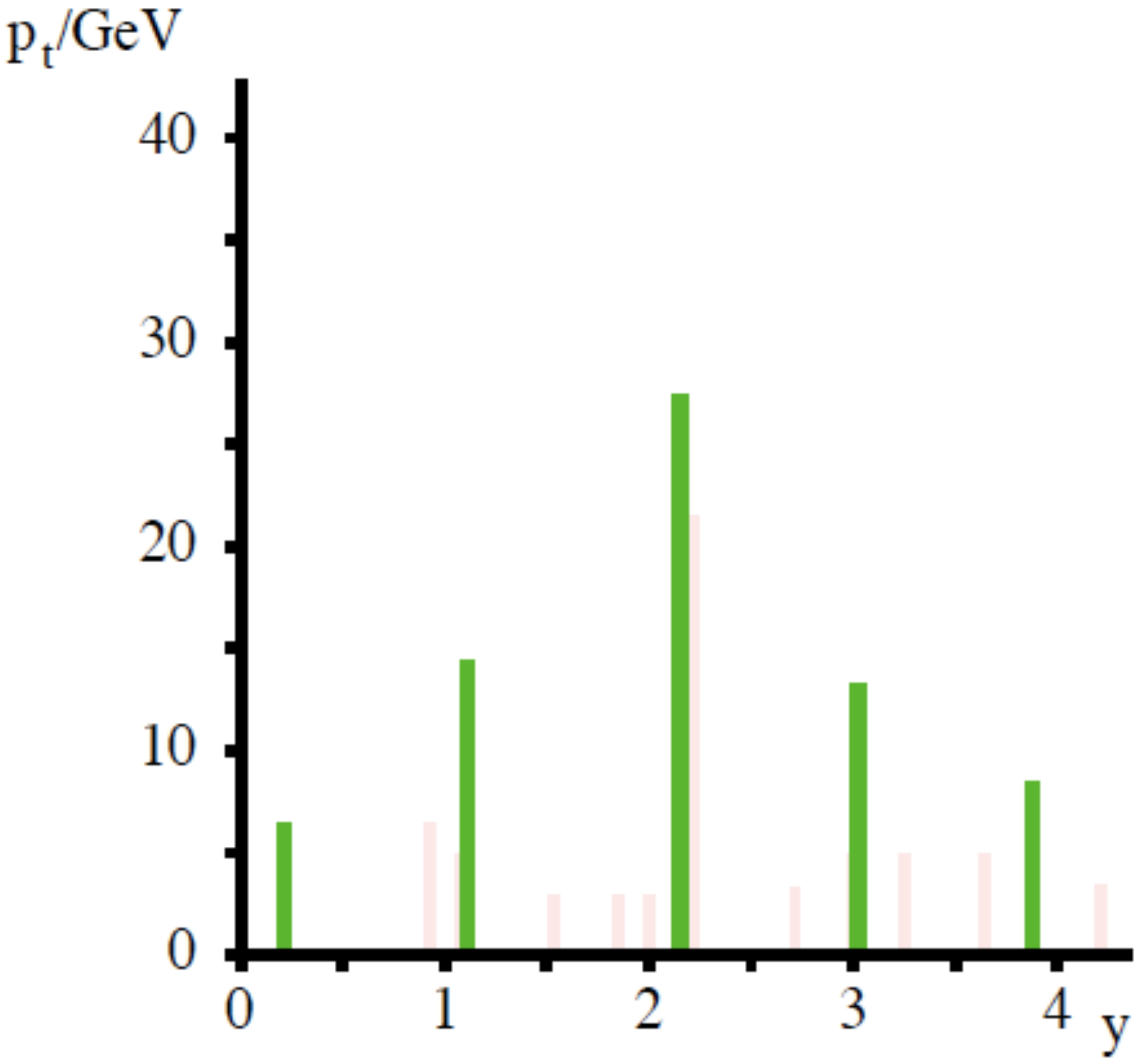

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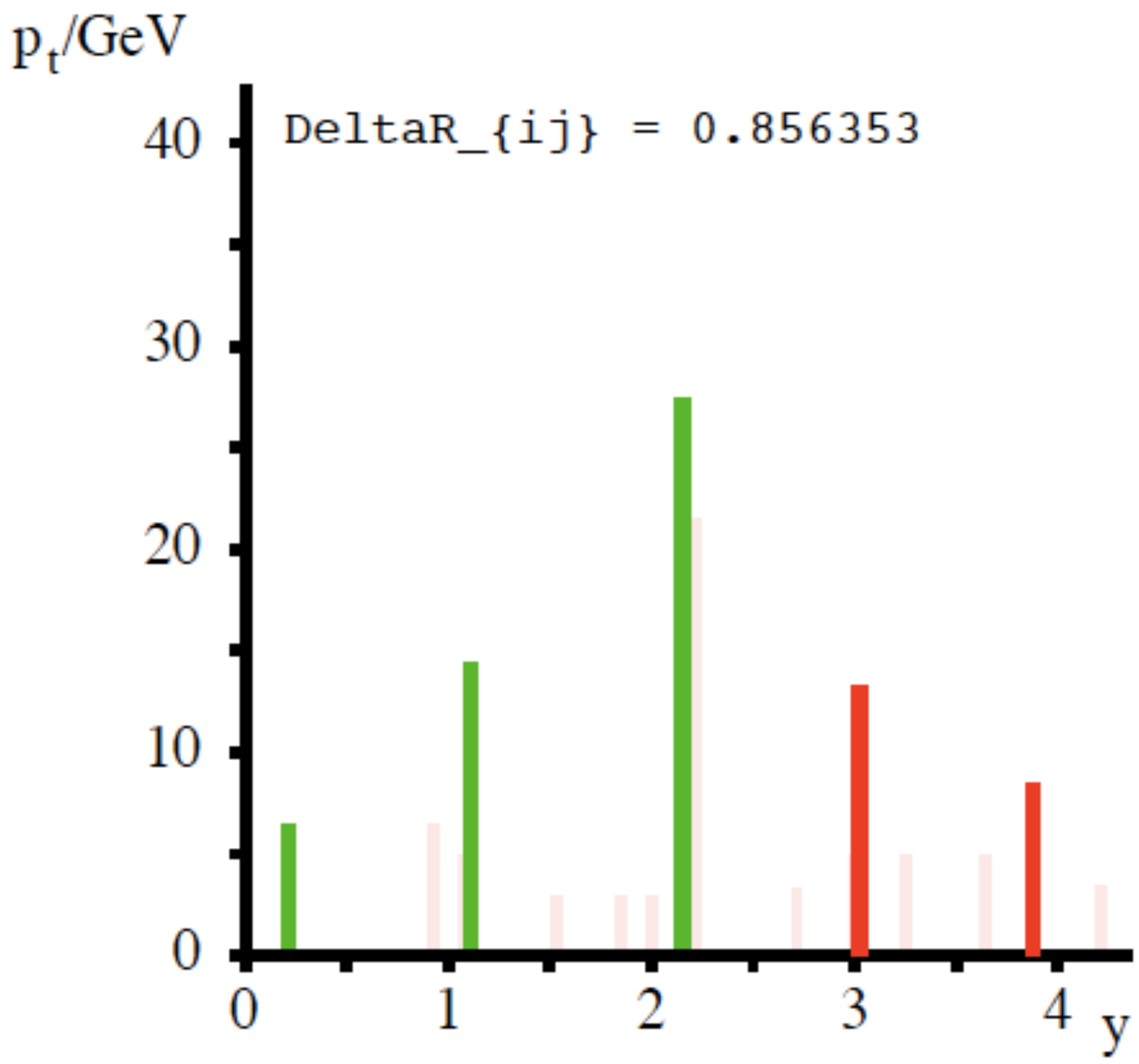

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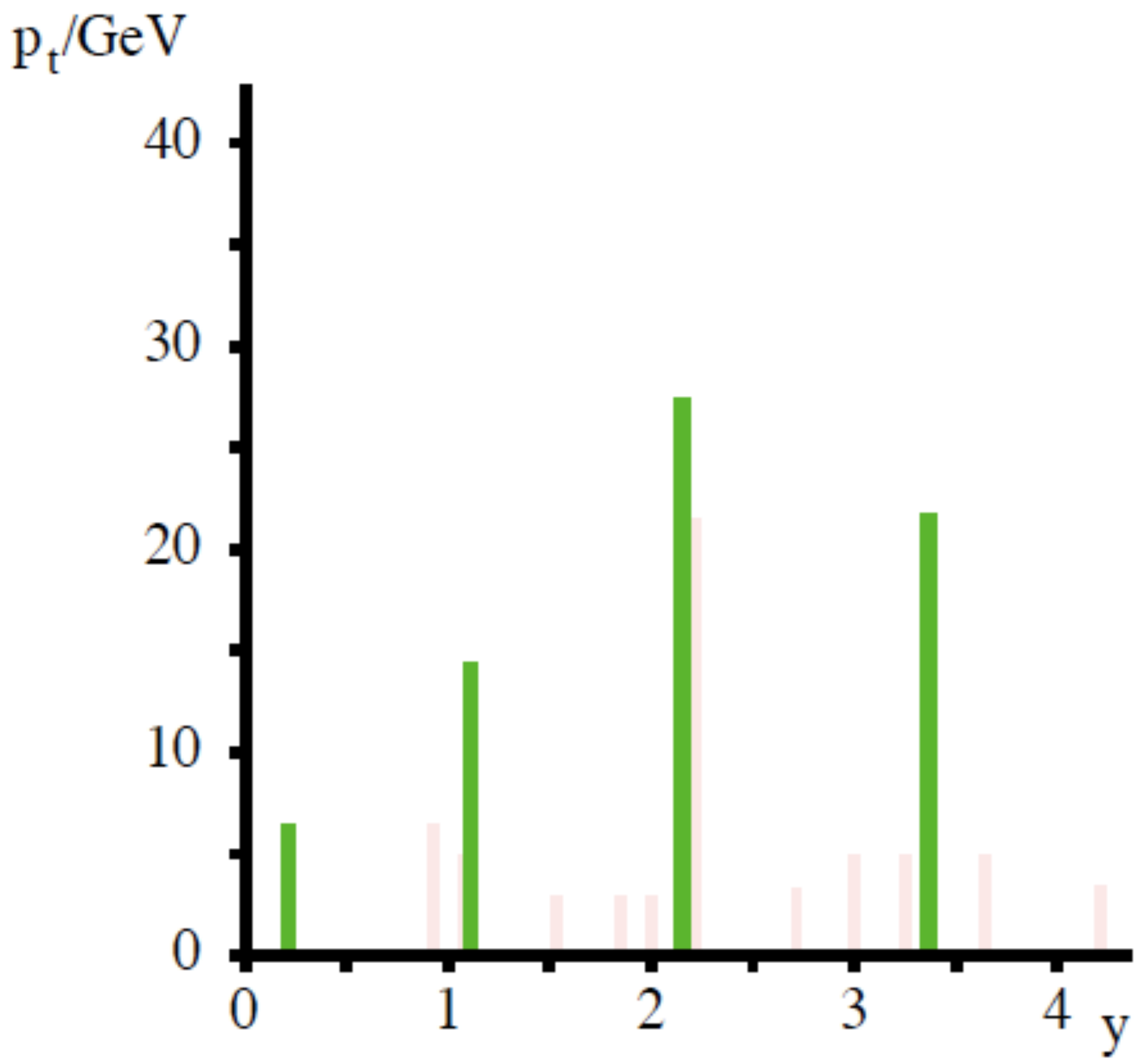

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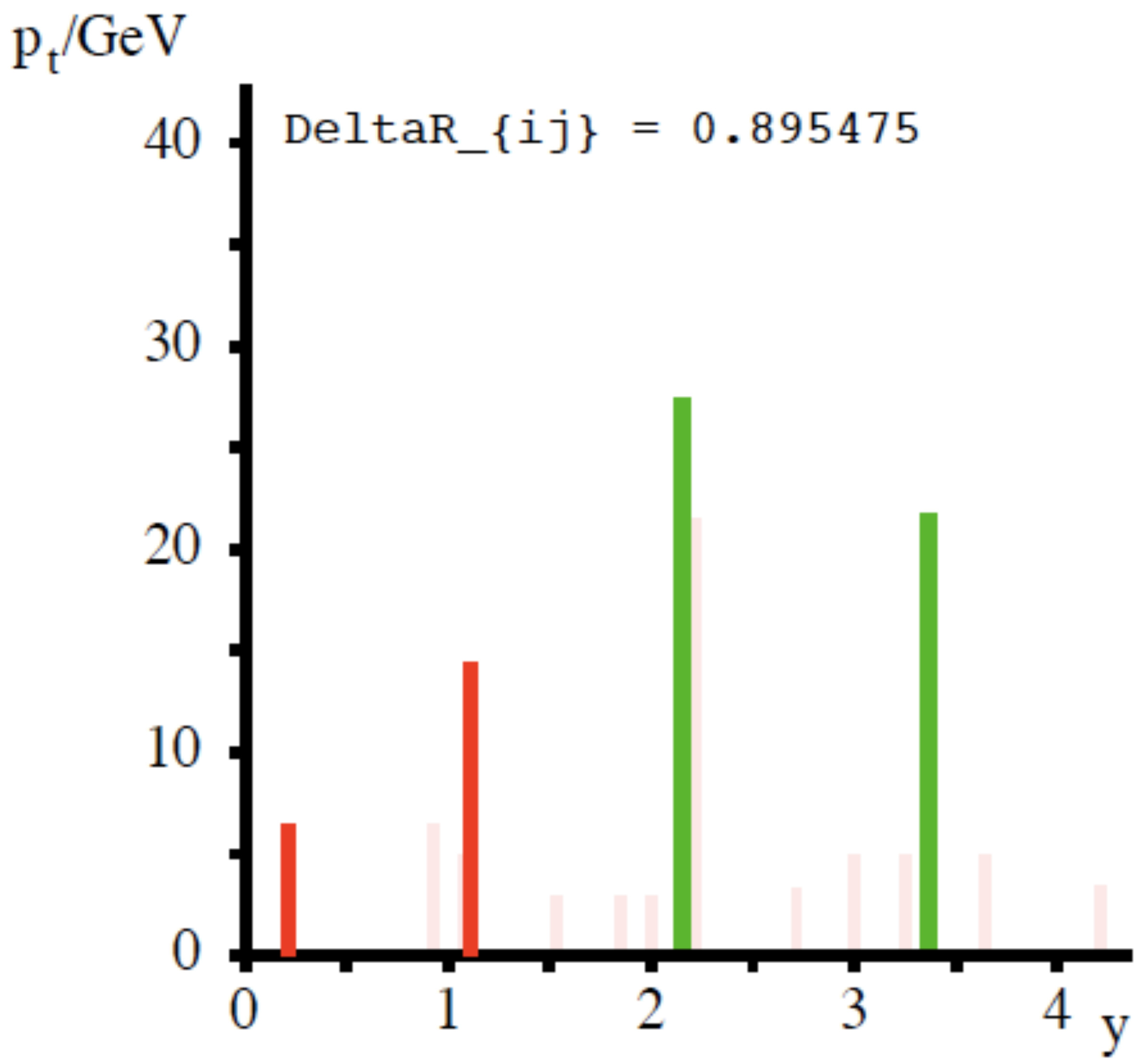

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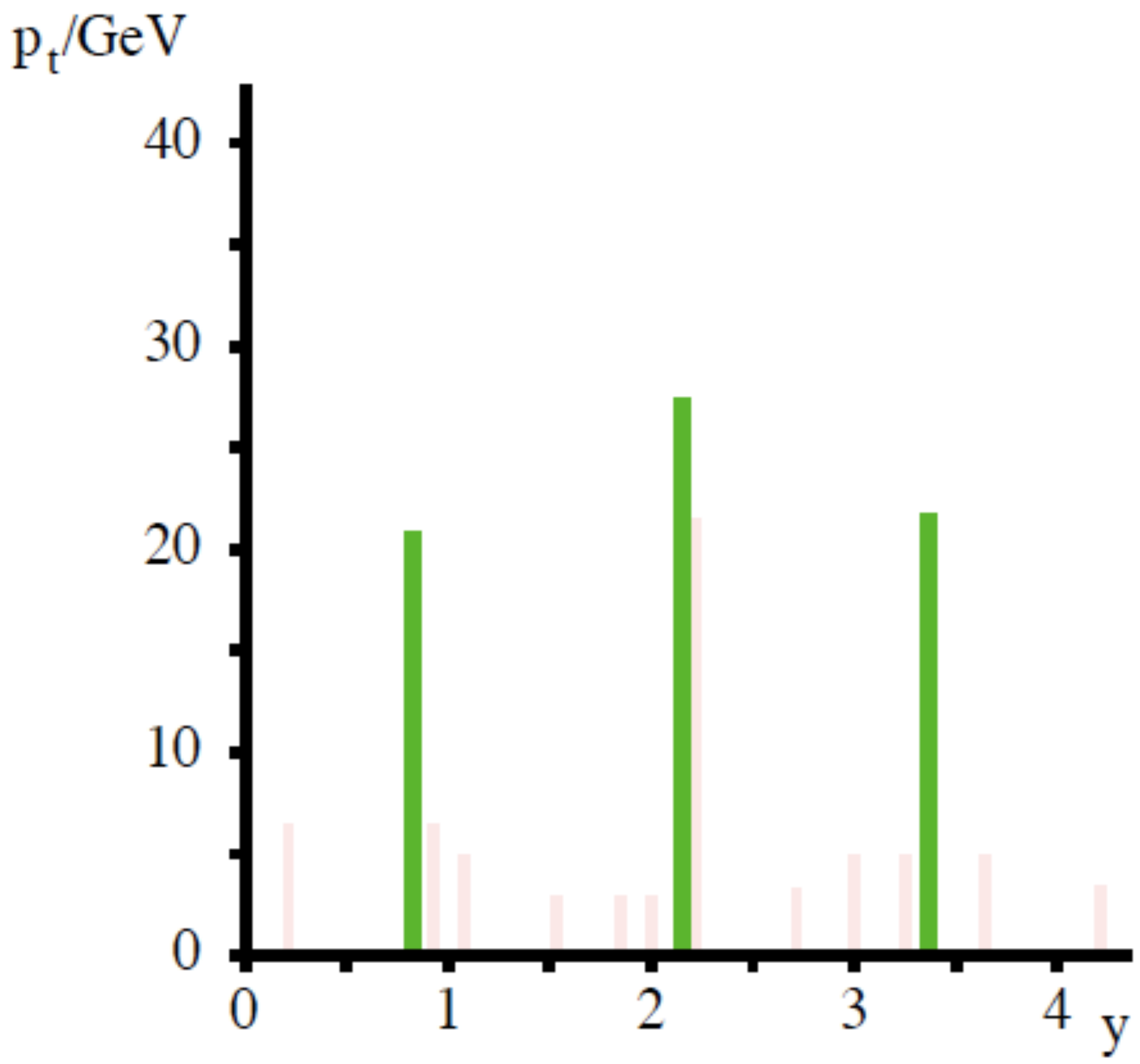

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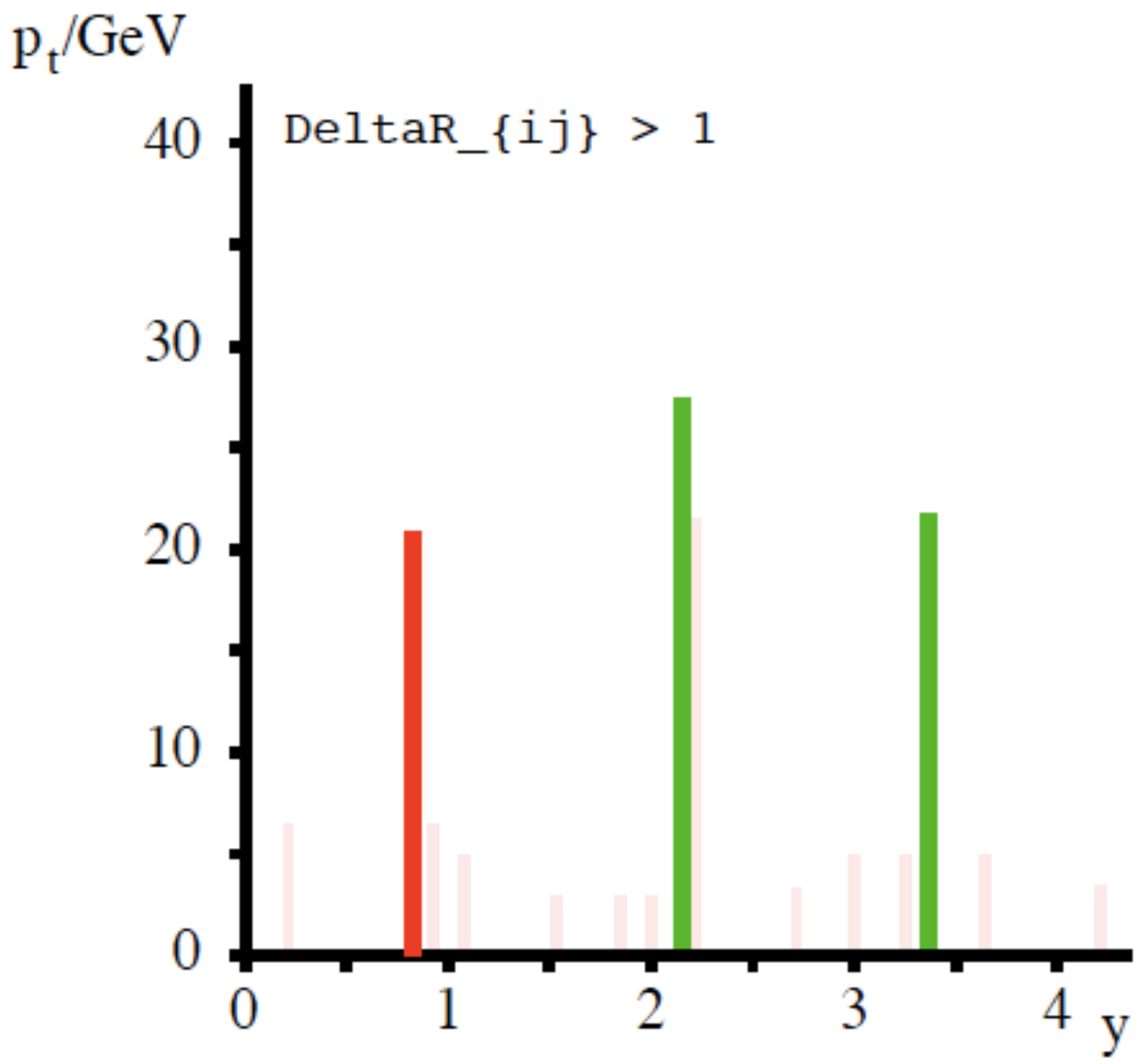

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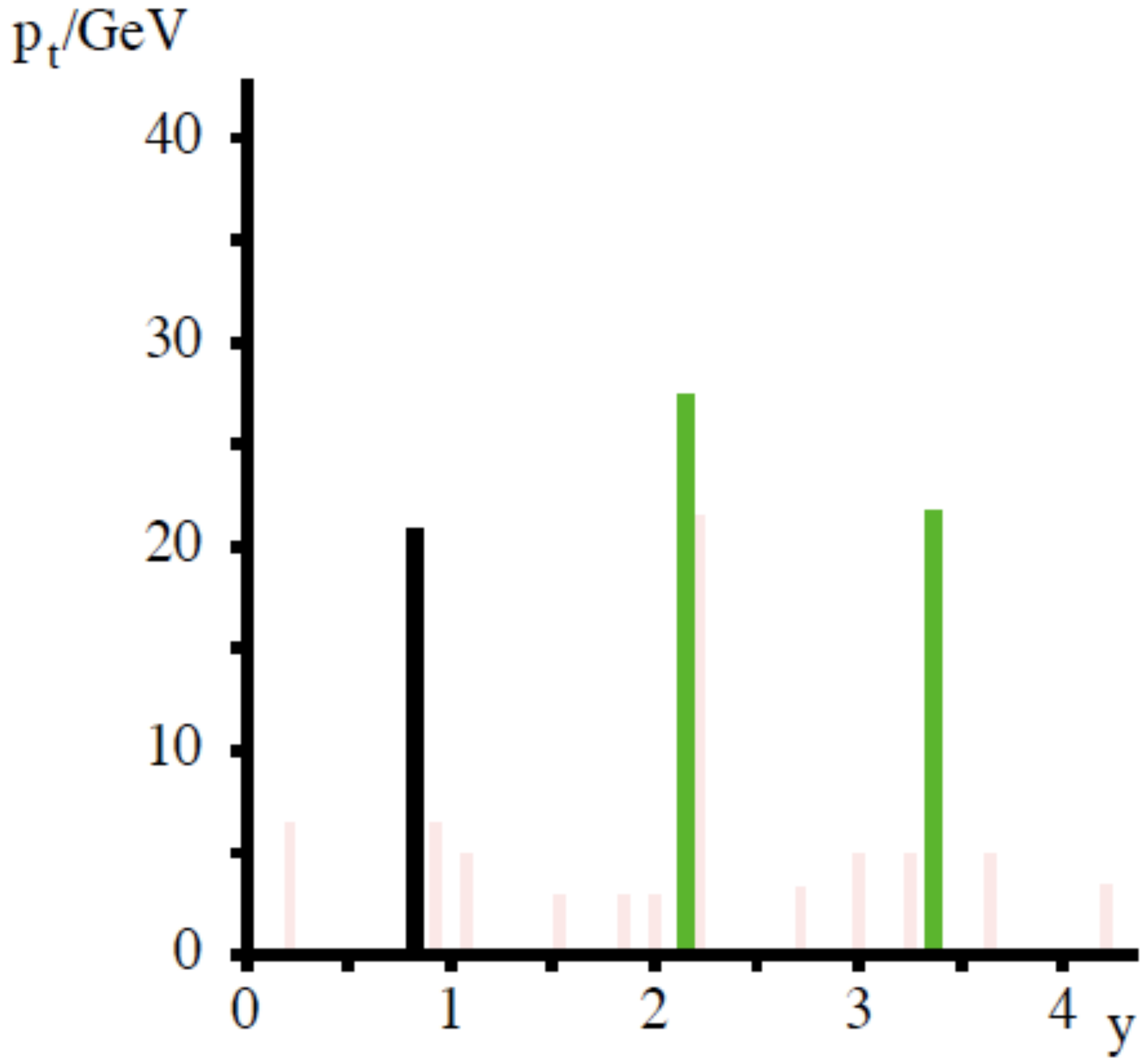

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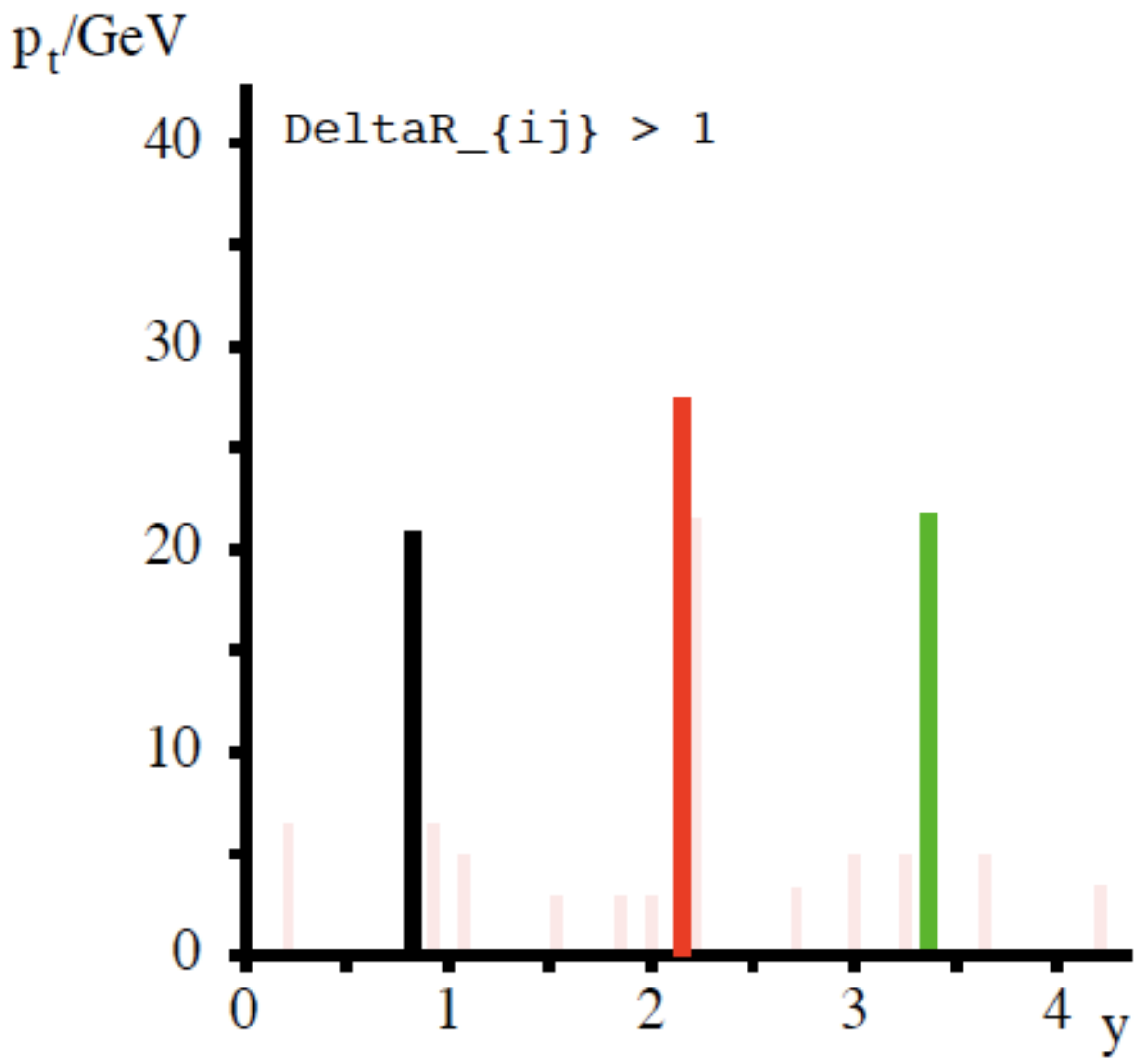

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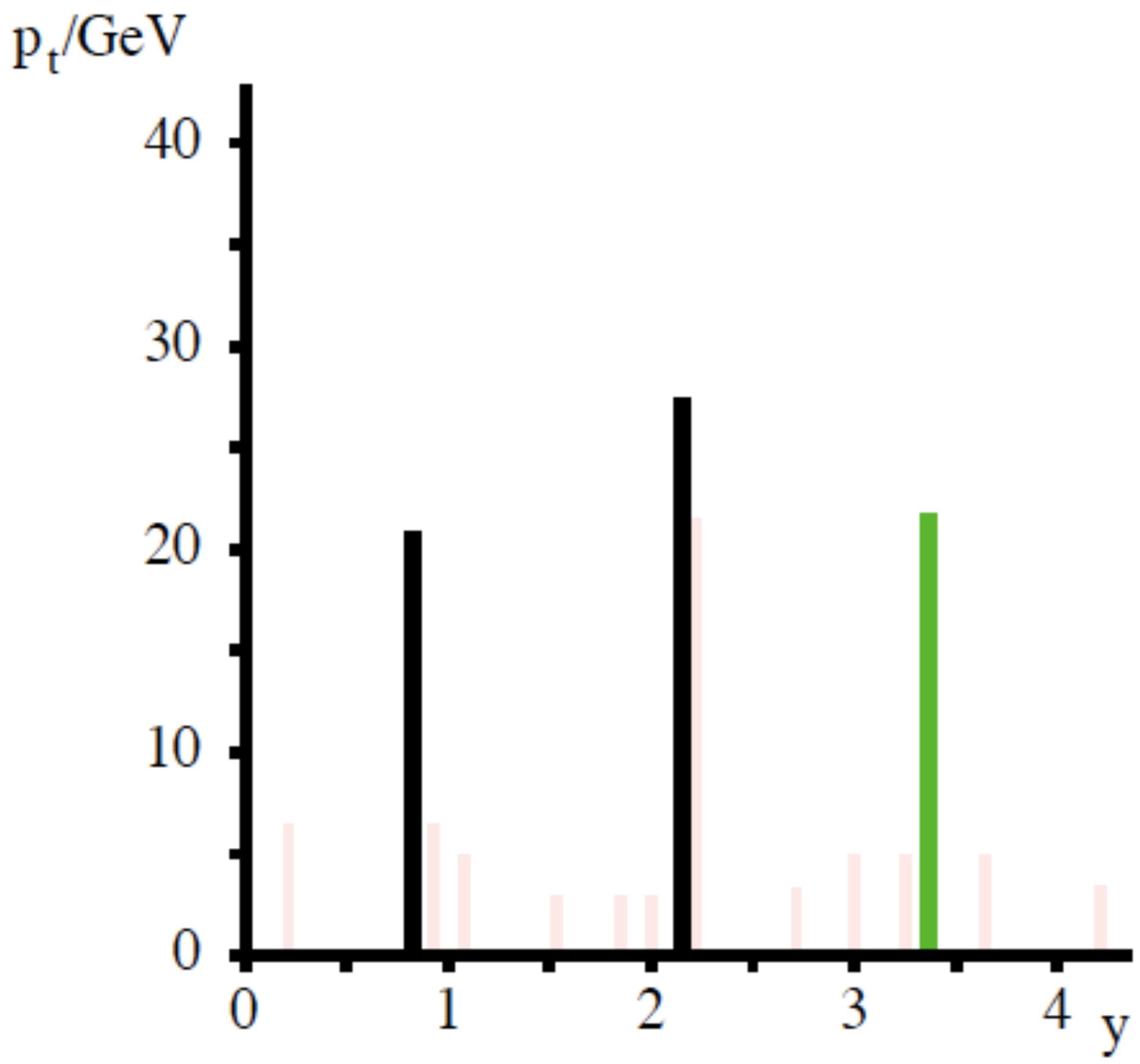

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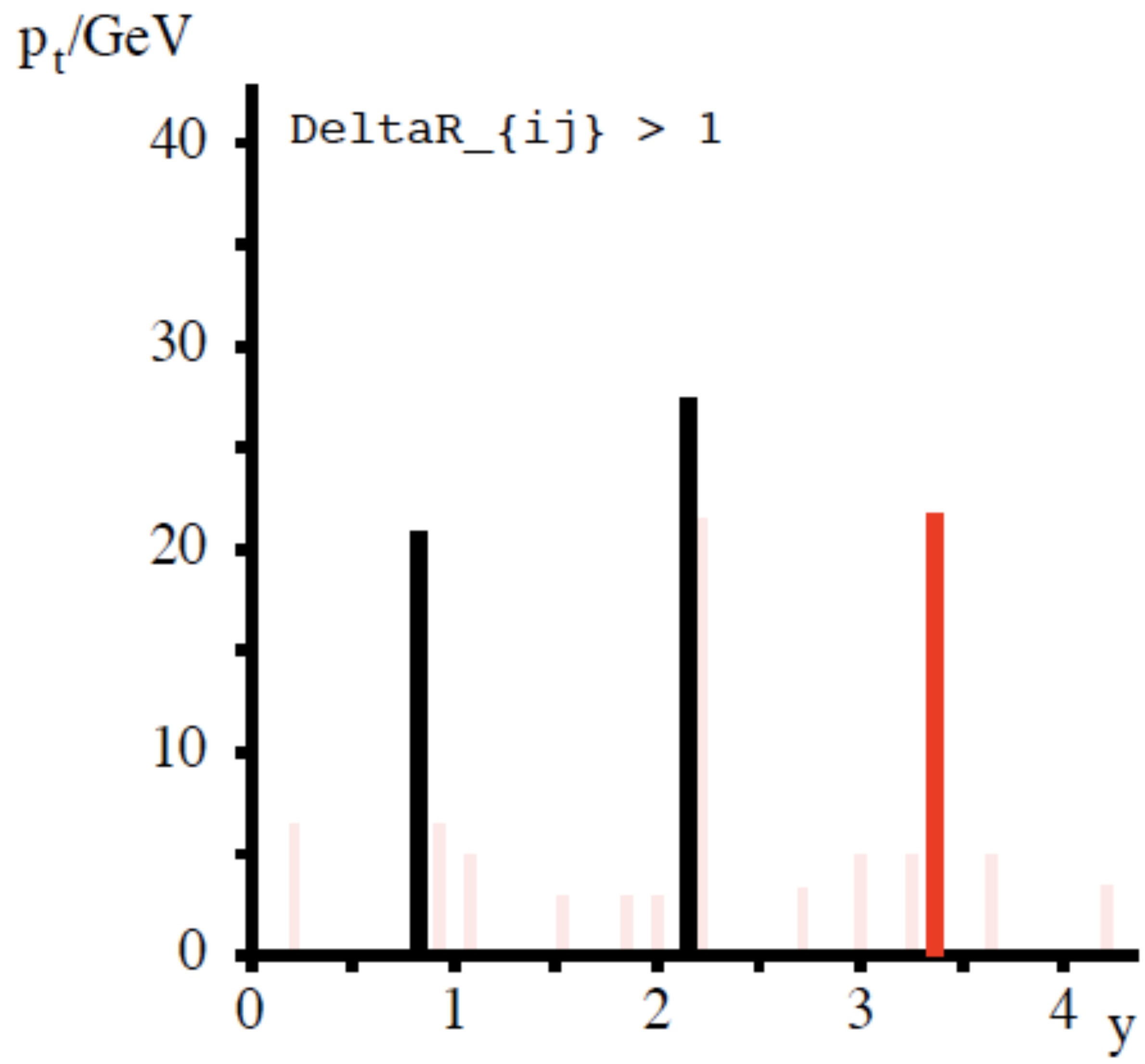

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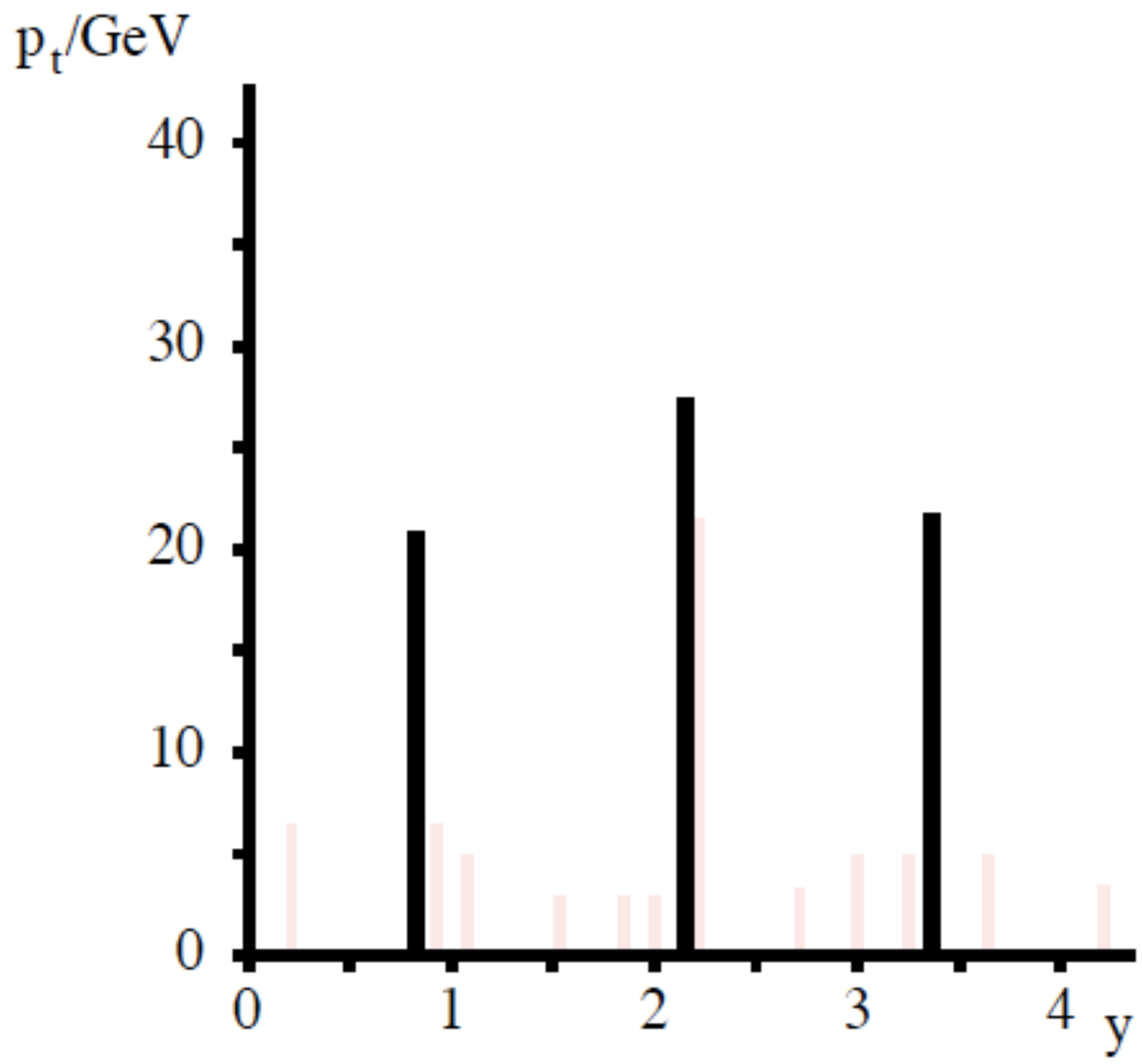
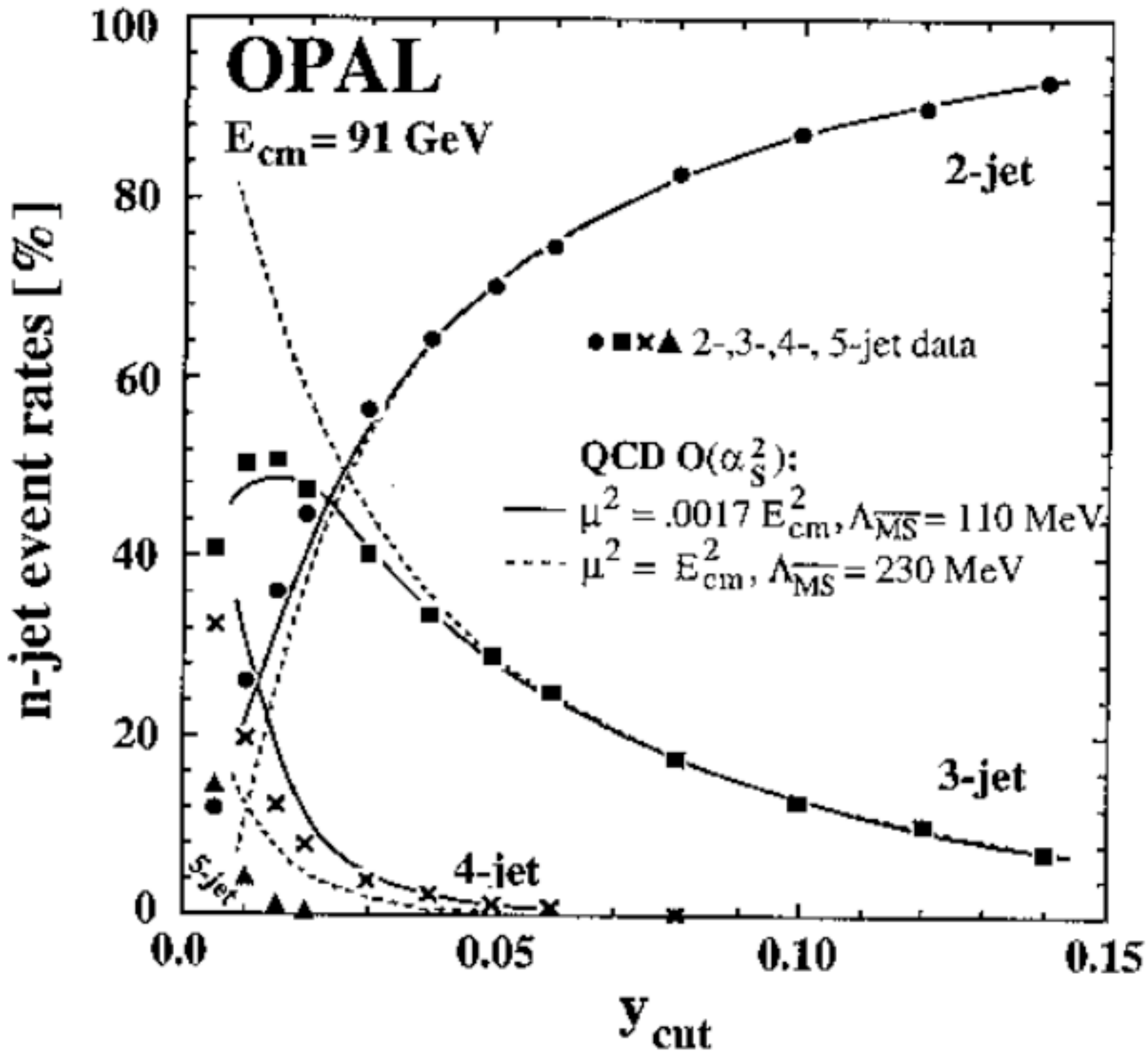


➩ This expression also describes well the y dependence



Jet production

- The basic expression for 2 to 2 processes is

$$\frac{d\sigma}{dp_T^2} = \sum_{ij} \int dx_1 dx_2 \, \frac{f_i(x_1, Q_F^2) f_j(x_2, Q_F^2)}{(1+\delta_{ij})} \times \frac{d\hat{\sigma}}{dp_T^2}$$

✢ In the jet–jet CMS $\Longrightarrow$ $dy_1 dy_2 dp_T^2 = \frac{1}{2} s dx_1 dx_2 d\cos\theta^*$

$$\frac{d^3\sigma}{dy_1 dy_2 dp_T^2} = \frac{1}{16\pi s^2} \sum_{ij} \frac{f_i(x_1, Q_F^2) f_j(x_2, Q_F^2)}{(1+\delta_{ij}) x_1 x_2} \times \overline{\sum} |M(ij \to kl)|^2$$

with

$$x_1 = \frac{x_T}{2} \, (e^{y_1} + e^{y_2}) \quad ; \quad x_2 = \frac{x_T}{2} \, (e^{-y_1} + e^{-y_2}) \qquad \mathbf{x_T} = \frac{\mathbf{2p_T}}{\sqrt{\mathbf{s}}}$$

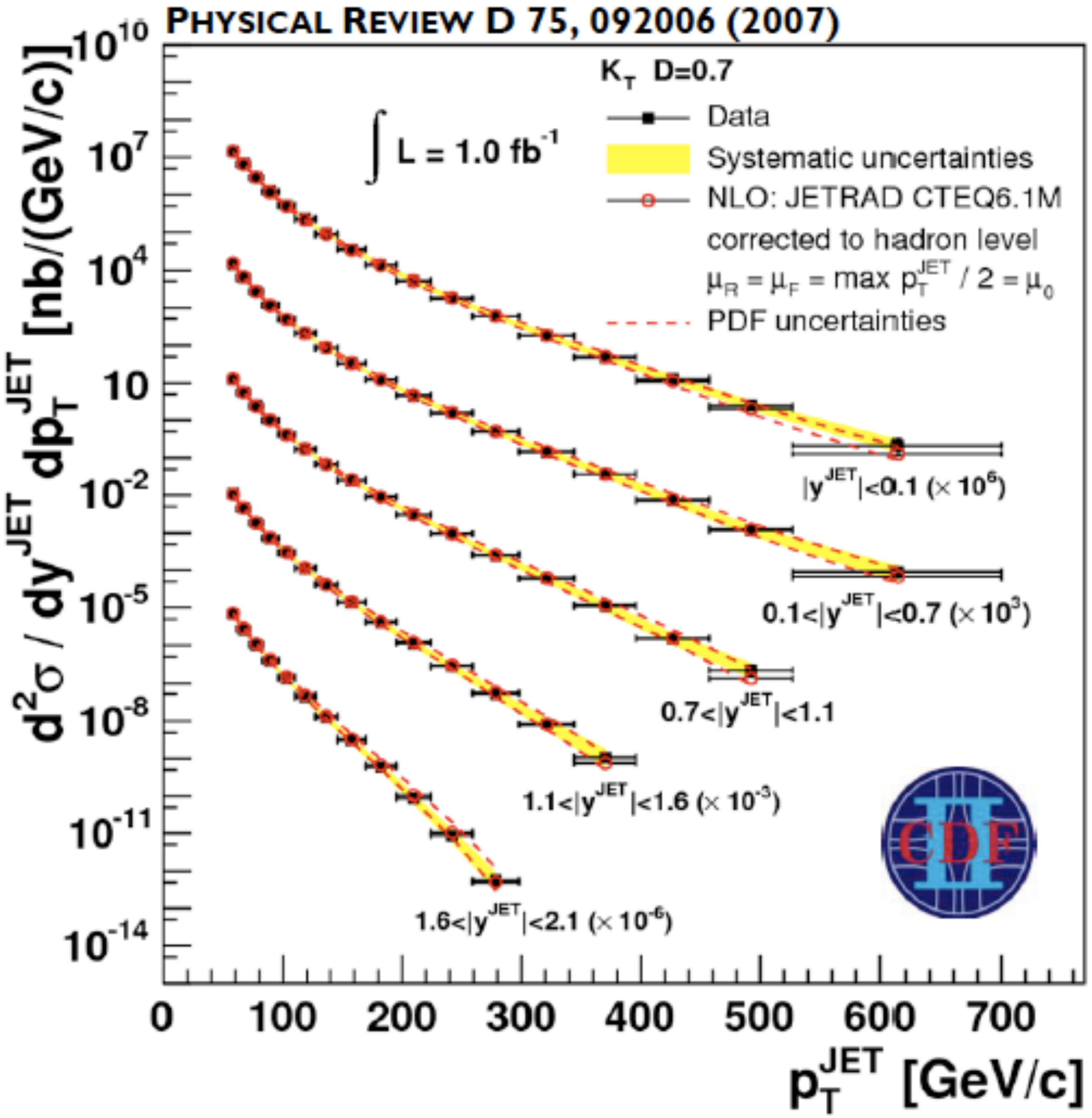
✢ The LO processes leading to jets are (gluon in the t–channel)

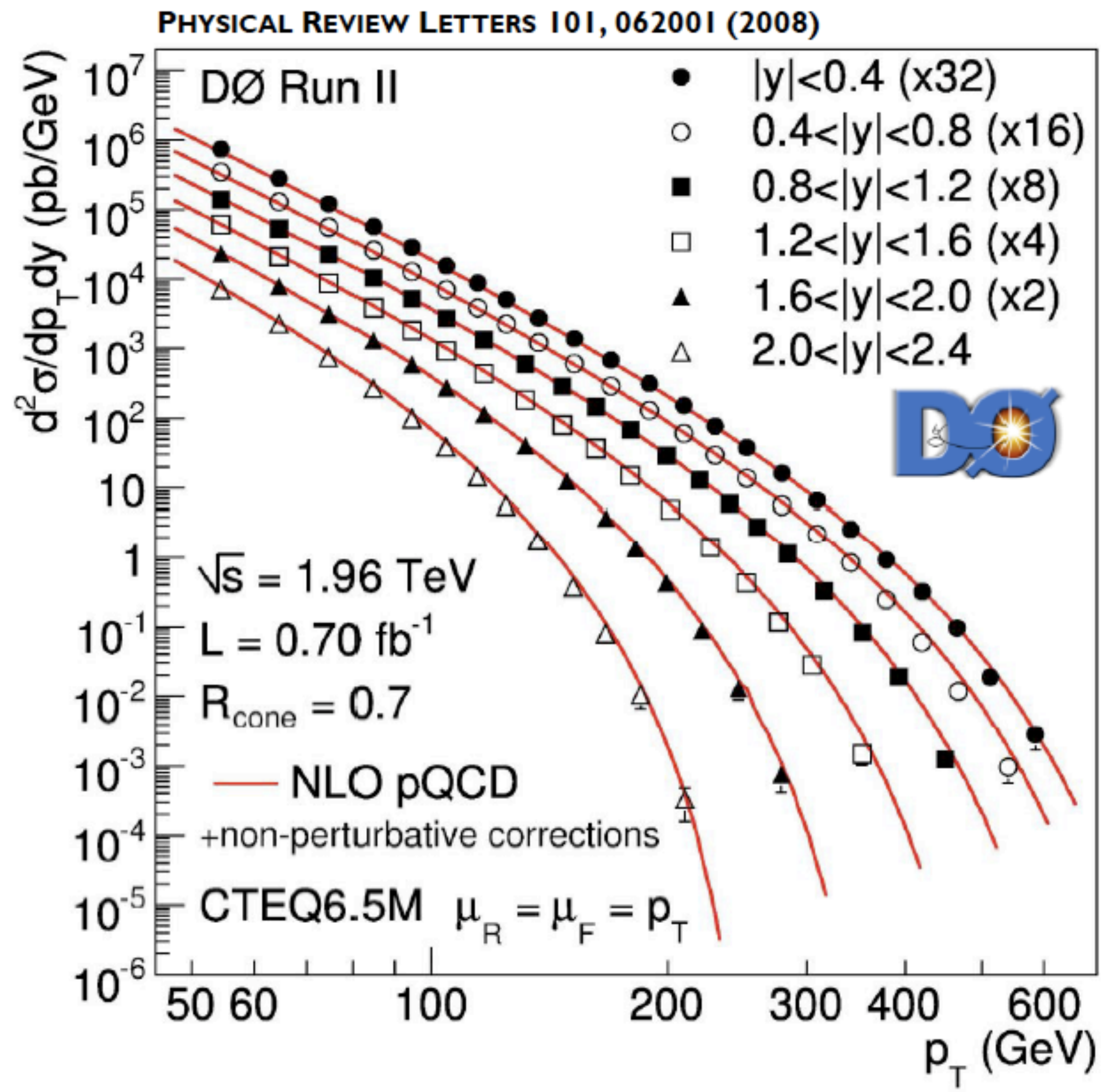
Process	$\frac{32\pi^2}{\alpha_s^2}\,\frac{d\hat{\sigma}}{d\Omega}$	at 90 degrees
$qq' \to qq'$	$\frac{1}{2\hat{s}}\,\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.2
$qq \to qq$	$\frac{1}{2}\,\frac{1}{2\hat{s}}\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\,\frac{\hat{s}^2}{\hat{u}\hat{t}}\right]$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{1}{2\hat{s}}\,\frac{4}{9}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{1}{2\hat{s}}\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\,\frac{\hat{u}^2}{\hat{s}\hat{t}}\right]$	2.6
$q\bar{q} \to gg$	$\frac{1}{2}\,\frac{1}{2\hat{s}}\left[\frac{32}{27}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$	1.0
$gg \to q\bar{q}$	$\frac{1}{2\hat{s}}\left[\frac{1}{6}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$	0.1
$gq \to gq$	$\frac{1}{2\hat{s}}\left[-\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right]$	6.1
$gg \to gg$	$\frac{1}{2}\,\frac{1}{2\hat{s}}\,\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$	30.4

with $\hat{t} = -\hat{s}\,(1-\cos\theta)/2$ and $\hat{u} = -\hat{s}\,(1+\cos\theta)/2$

Tevatron results

the inclusive jet cross section does agree with NLO QCD over 8 orders of magnitude!





• Let's look the results without the dirt trick of log plots

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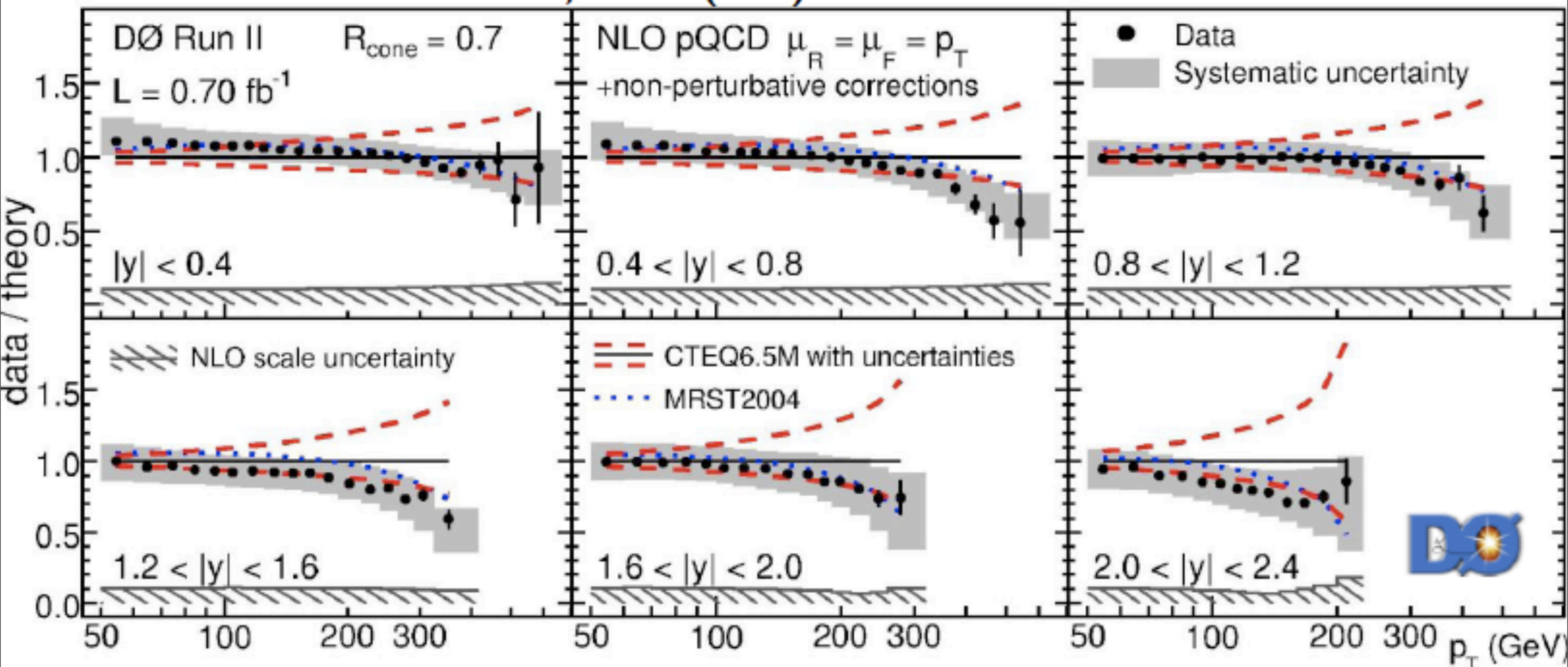
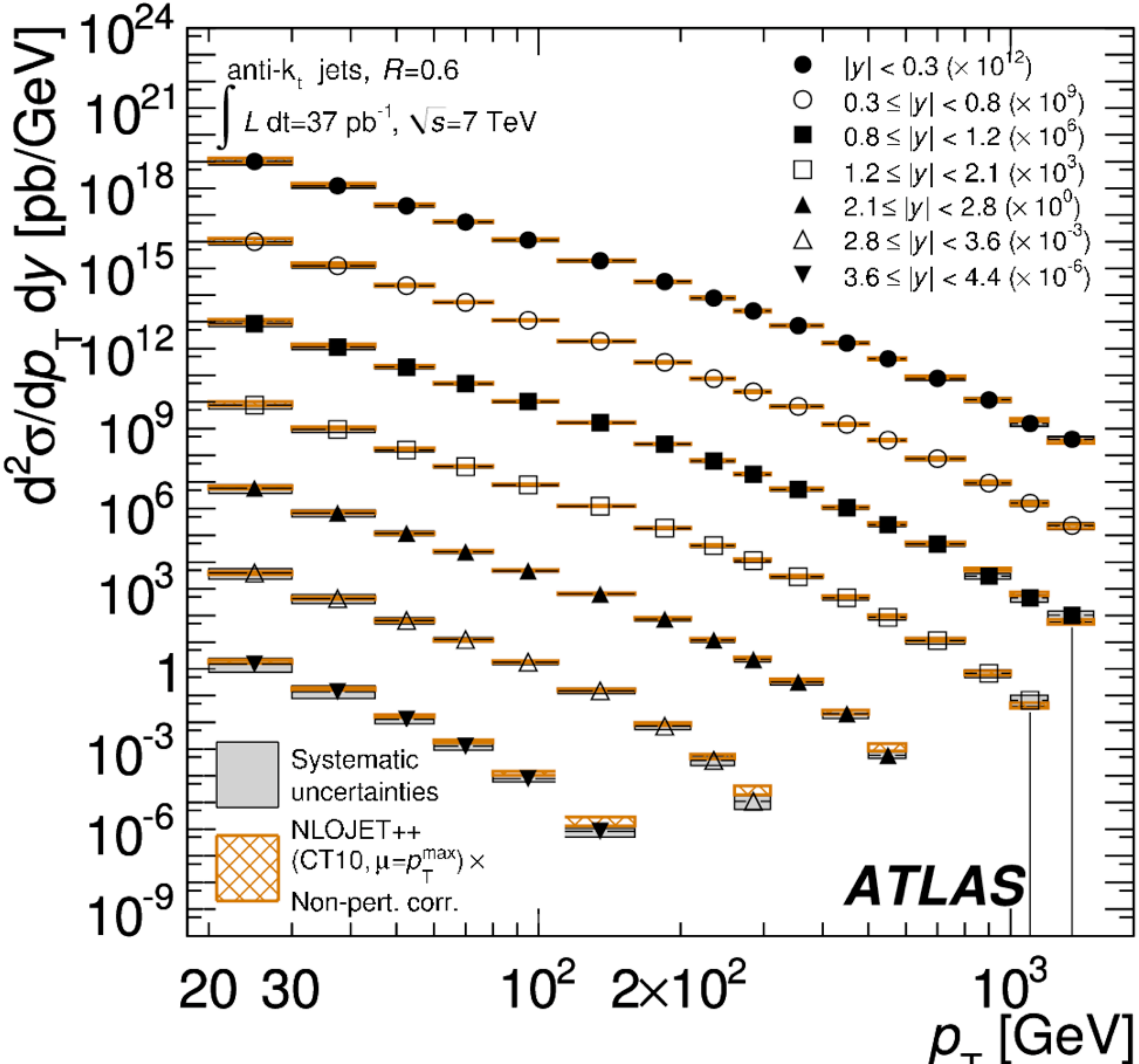
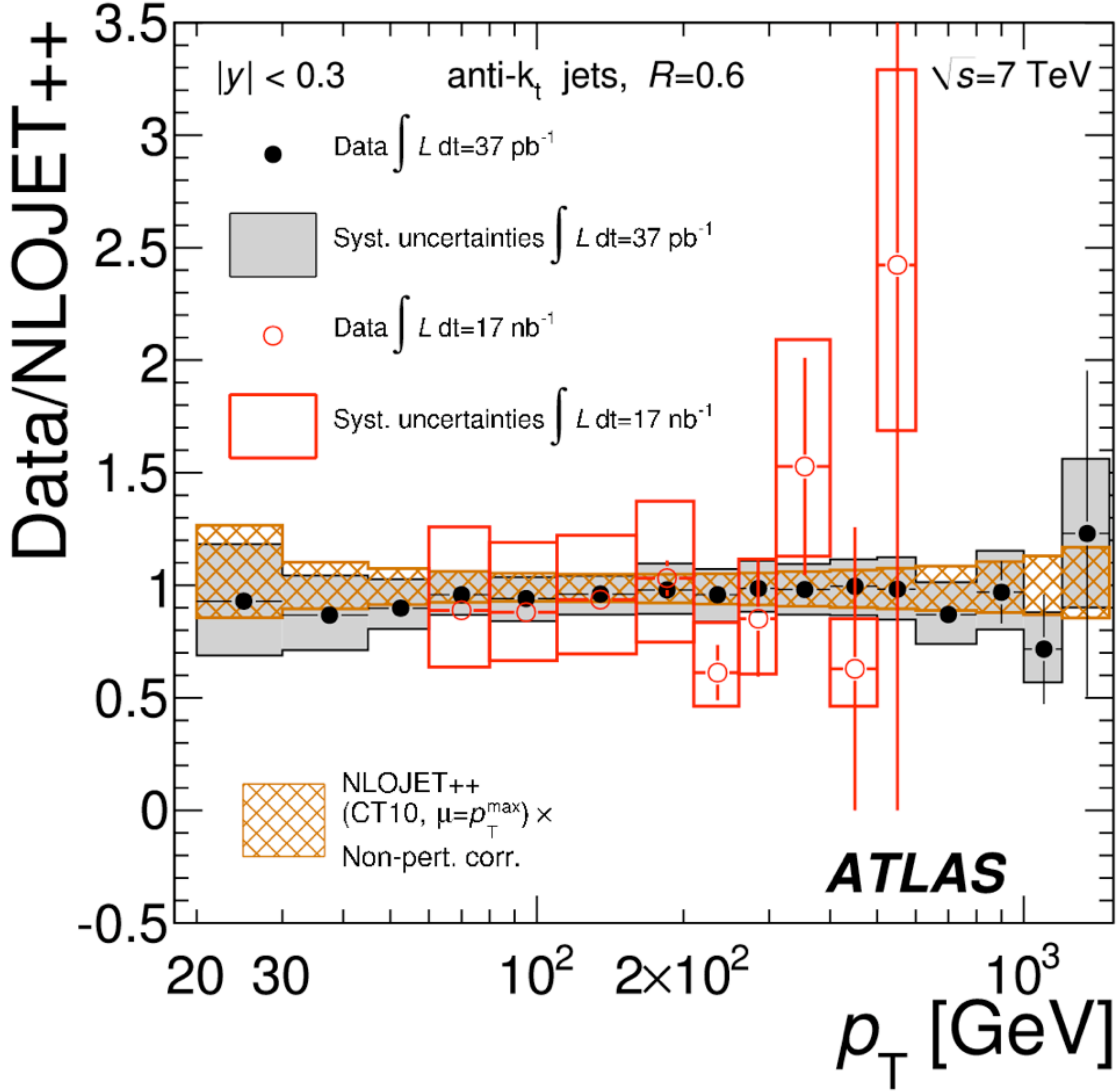


Jets at the LHC

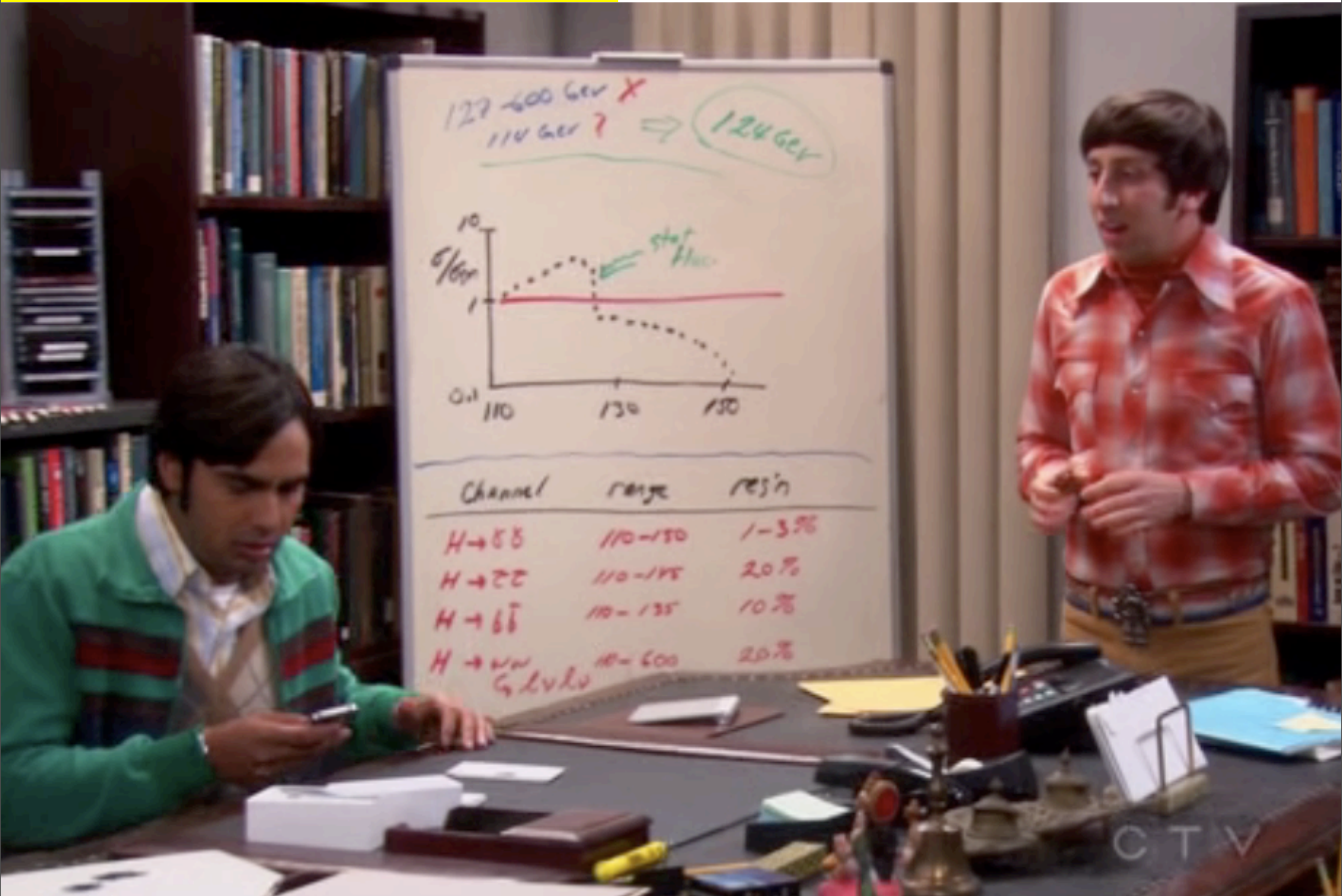
the inclusive jet cross section is nicely described by NLO QCD



a more serious comparison

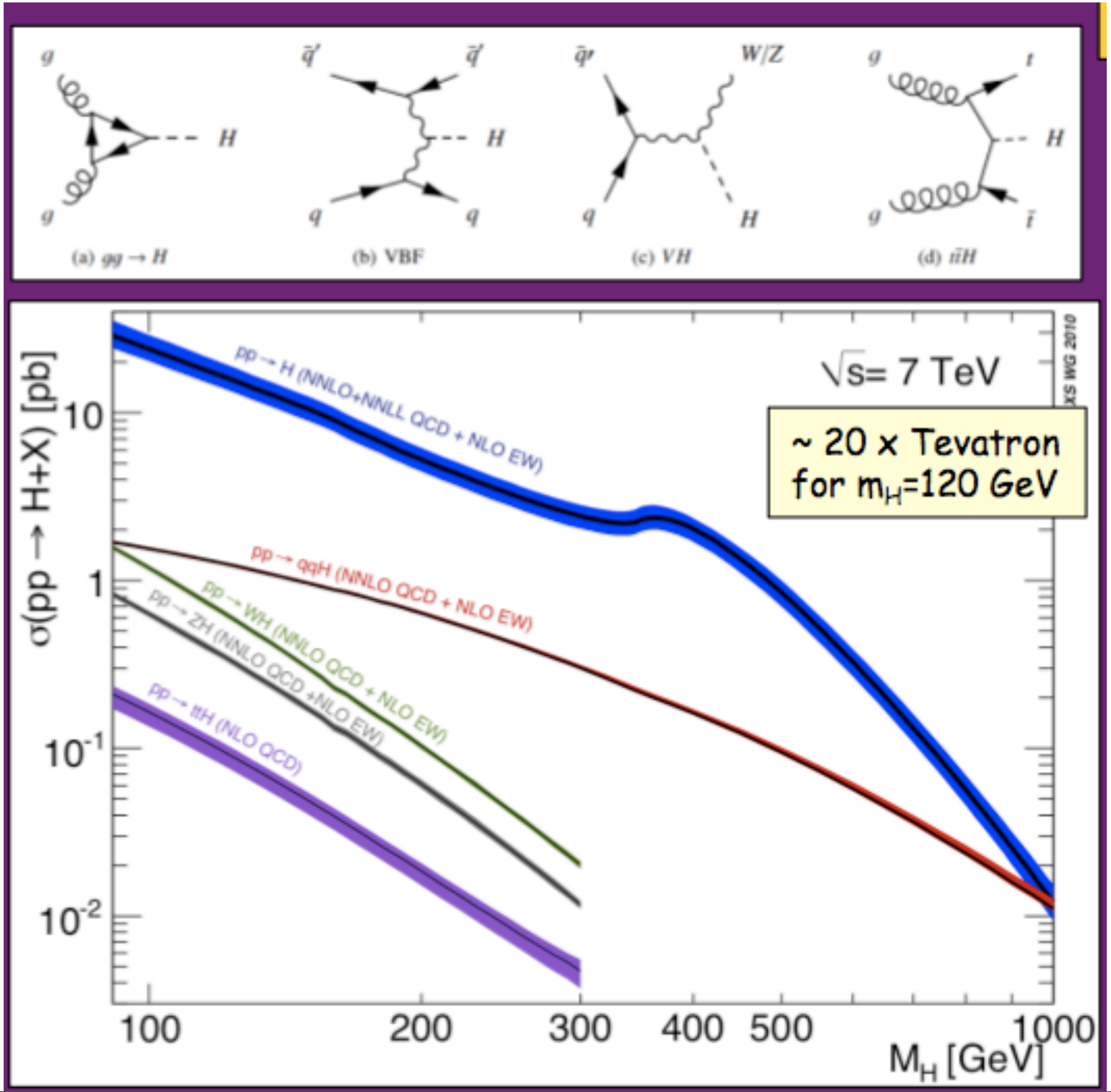


V. Hunting the SM Higgs

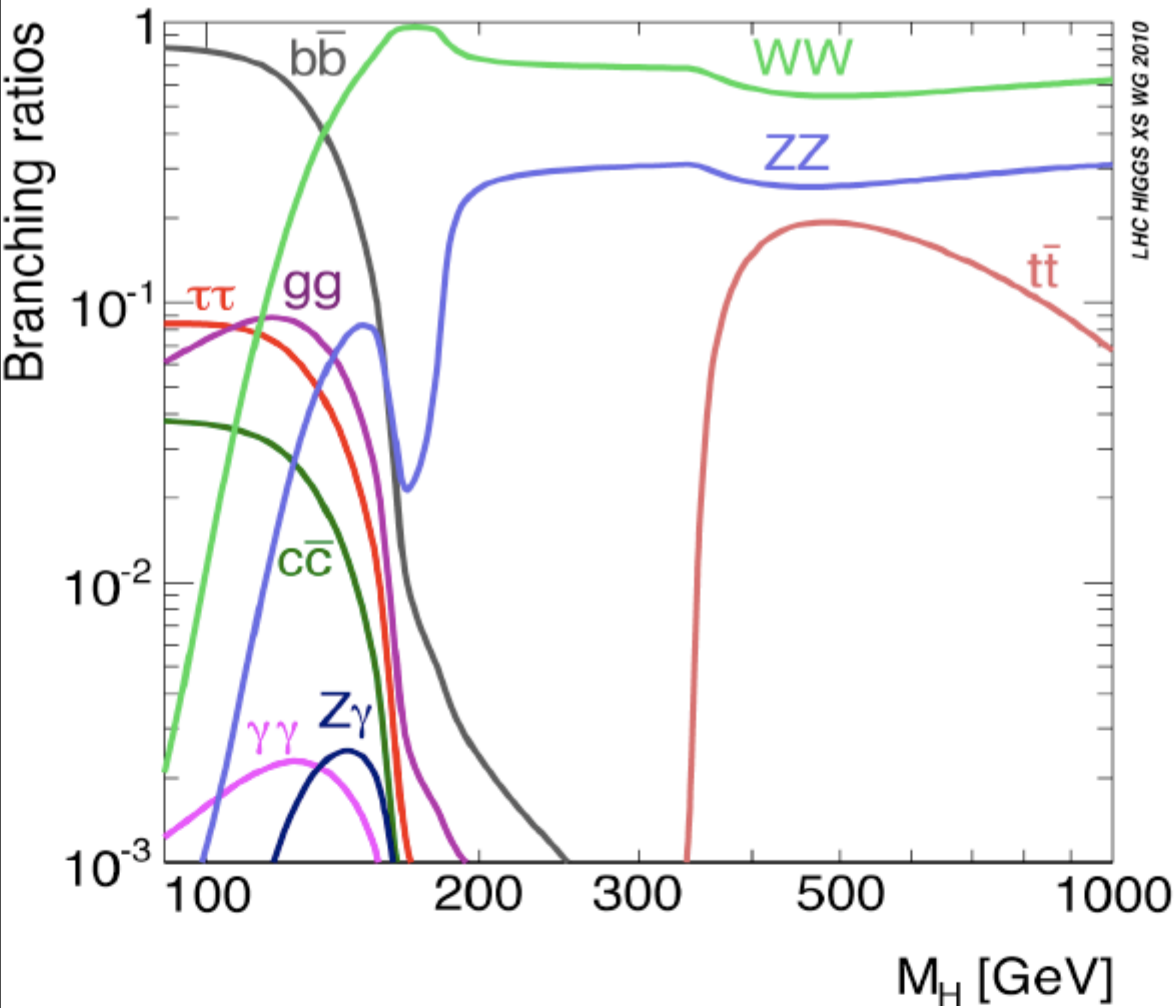


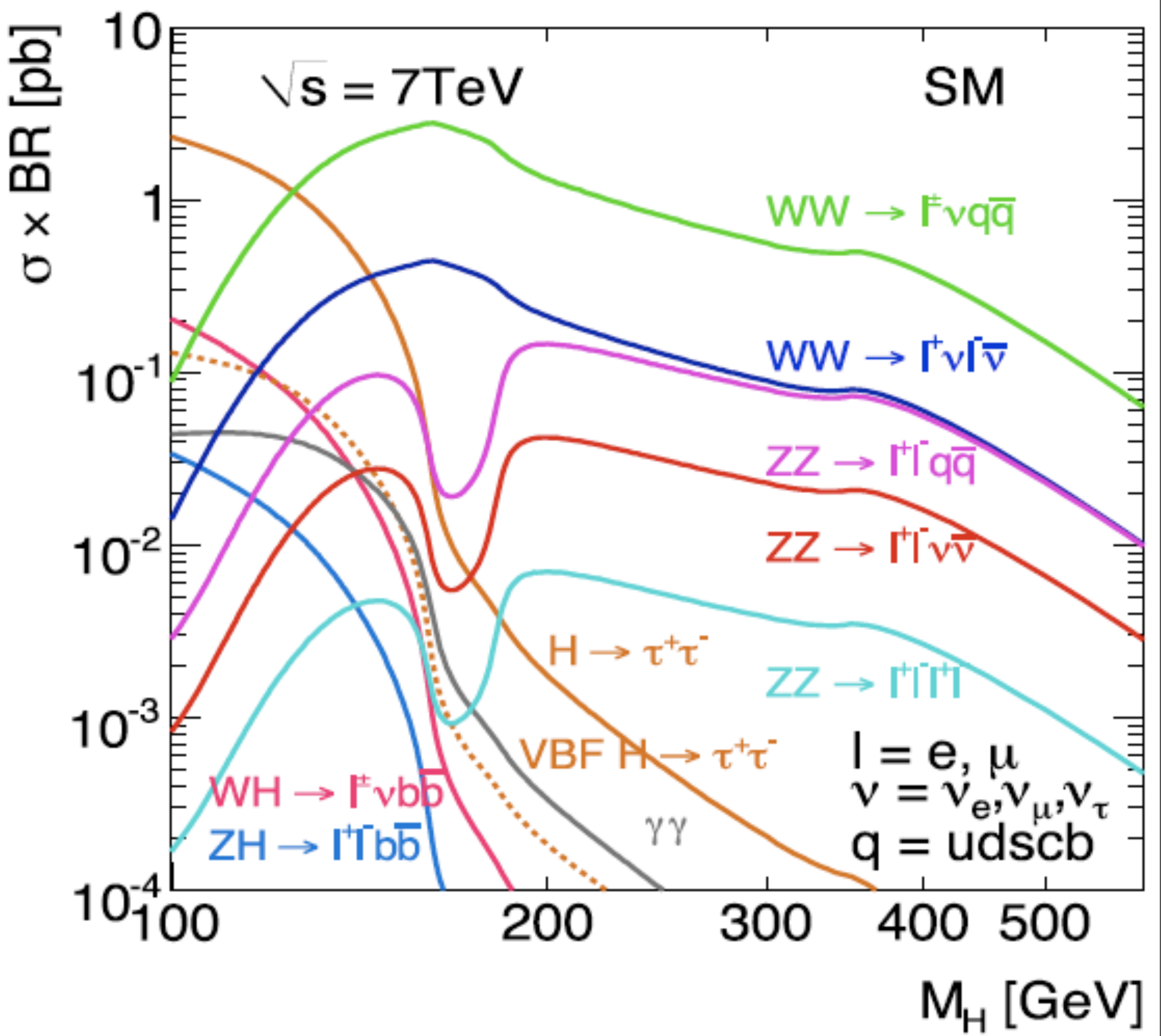
V. Hunting the SM Higgs

- Higgs production mechanisms and cross sections



- We must take into account the H decays





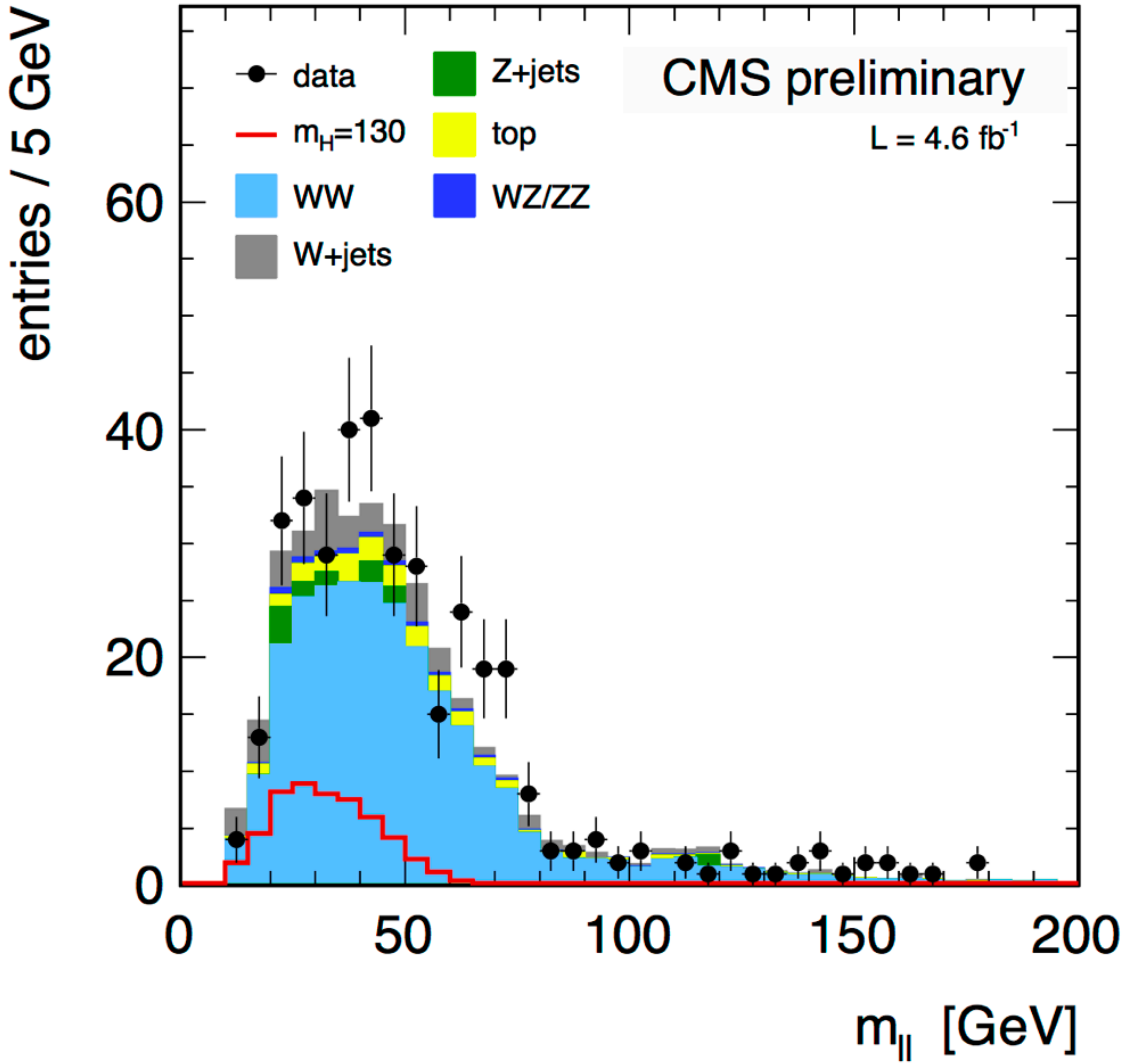
$H \to W^+W^- \to \ell^+\ell^-\not{E}_T \ + \ 0, 1, 2$ jets

- Cuts used in the analyses

m_{H}	$p_{\mathrm{T}}^{\ell,\max}$	$p_{\mathrm{T}}^{\ell,\min}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	$m_{T}^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}}$
[GeV/c^2]	[GeV/c]	[GeV/c]	[GeV/c^2]	[dg.]	[GeV/c^2]
	>	>	<	<	[,]
120	20	10(15)	40	115	[80,120]
130	25	10(15)	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]

$H \to W$

- Cuts us



CMS preliminary
L = 4.6 fb⁻¹
data
m_H=130
WW
W+jets
Z+jets
top
WZ/ZZ
entries / 5 GeV
m_{ll} [GeV]
0
20
40
60
0
50
100
150
200

$H \to W^+W^- \to \ell^+\ell^- \not{E}_T \; + \; 0, 1, 2$ jets

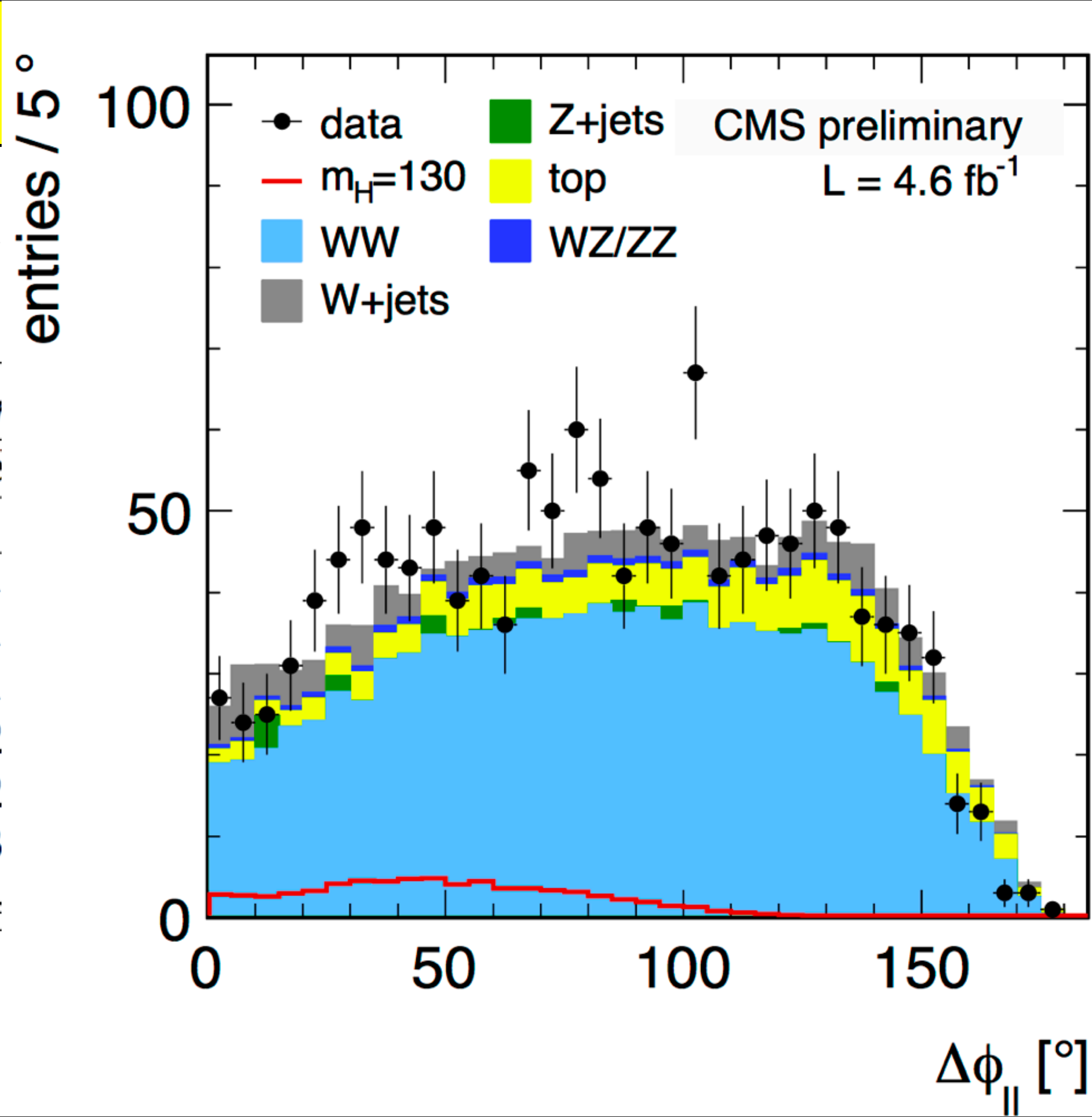
- Cuts used in the analyses

m_{H}	$p_{\mathrm{T}}^{\ell,\mathrm{max}}$	$p_{\mathrm{T}}^{\ell,\mathrm{min}}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	$m_T^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}}$
[GeV/c^2]	[GeV/c]	[GeV/c]	[GeV/c^2]	[dg.]	[GeV/c^2]
	$>$	$>$	$<$	$<$	[,]
120	20	10(15)	40	115	[80,120]
130	25	10(15)	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]

$H \to W$

- Cuts us

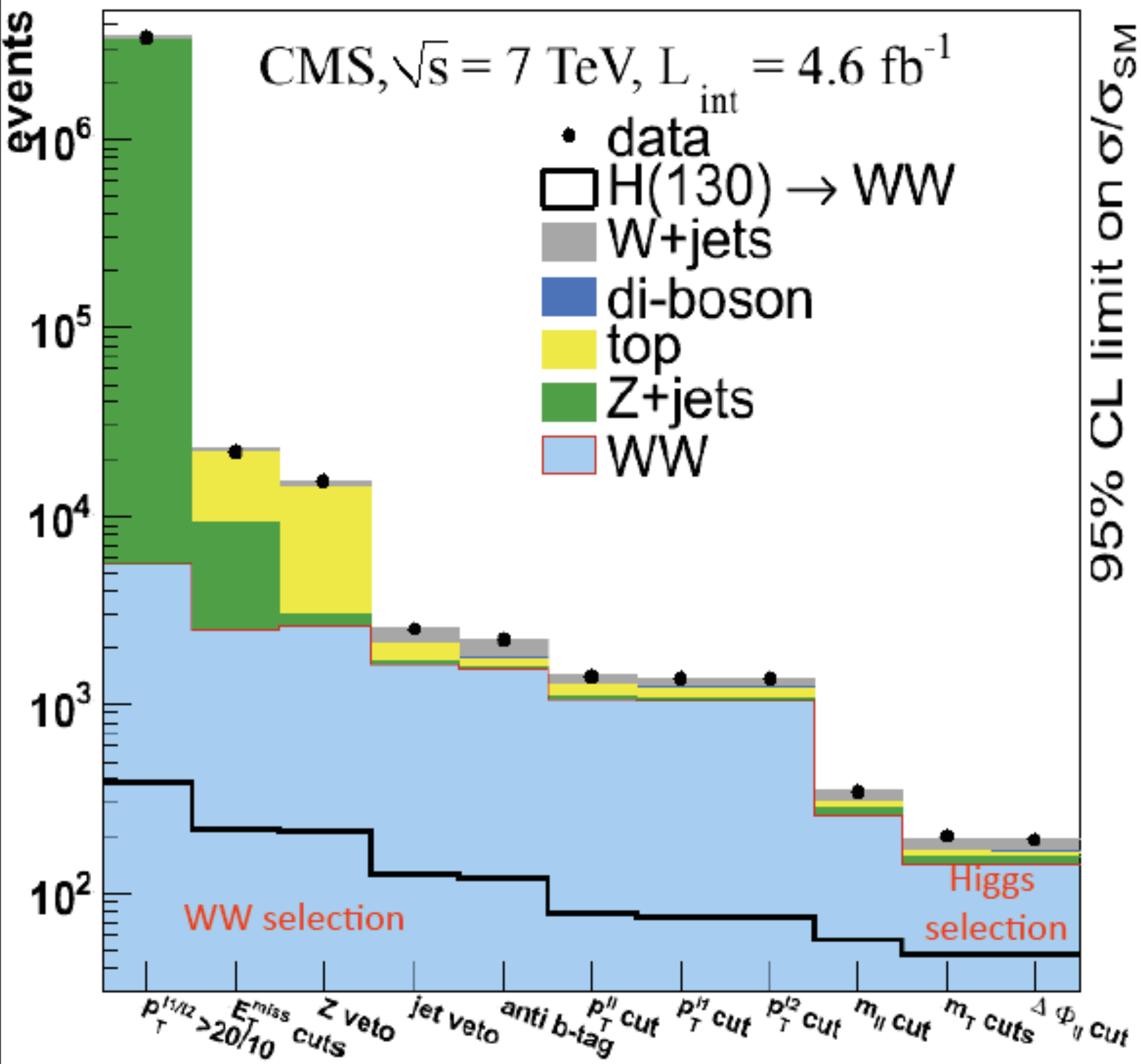
m
[Ge
1
1
1
2
2
3
4

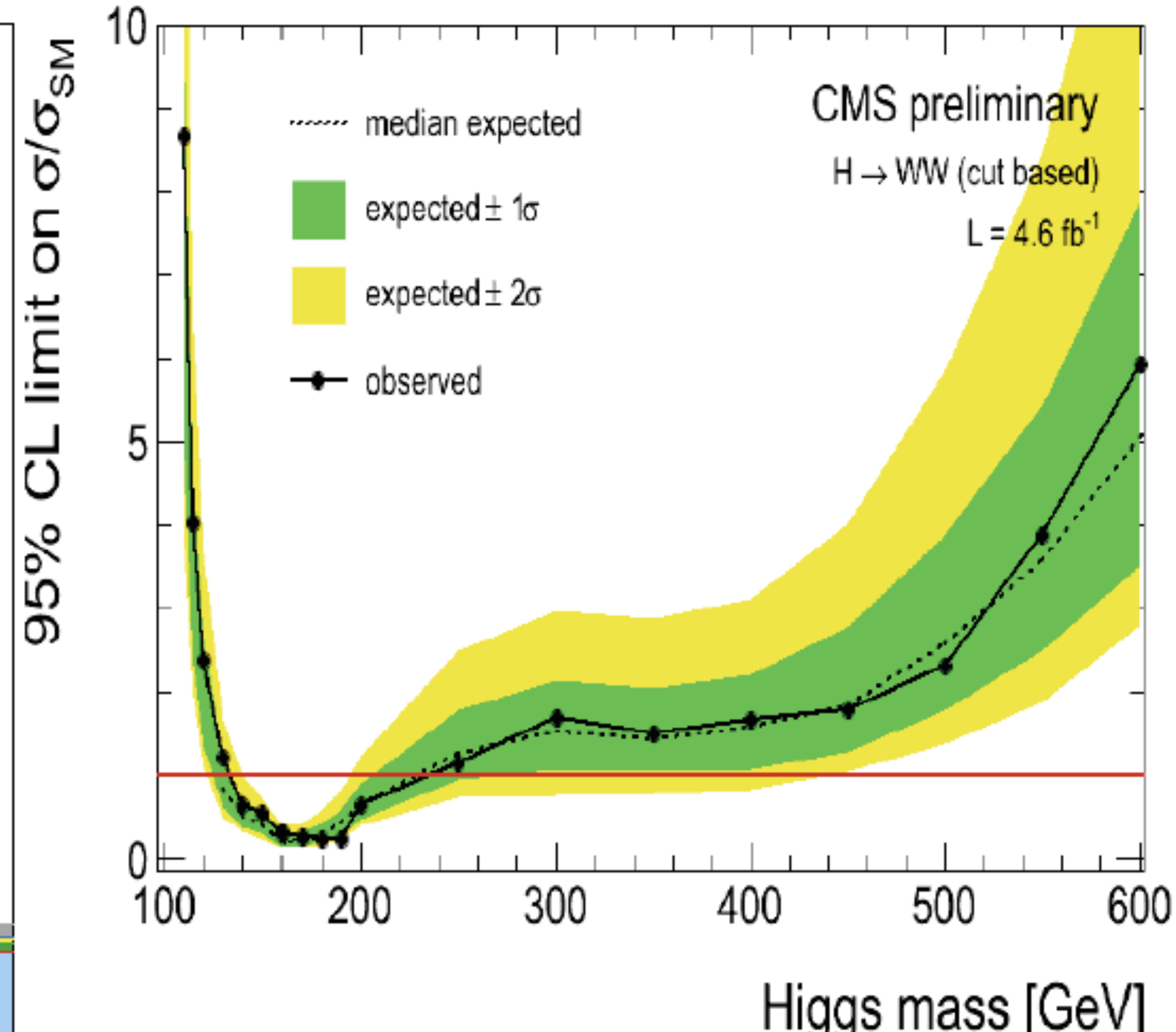


$H \to W^+W^- \to \ell^+\ell^-\not\!\!E_T \; + \; 0, 1, 2$ jets

- Cuts used in the analyses

m_{H}	$p_{\mathrm{T}}^{\ell,\mathrm{max}}$	$p_{\mathrm{T}}^{\ell,\mathrm{min}}$	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	$m_{T}^{\ell\ell E_{\mathrm{T}}^{\mathrm{miss}}}$
[GeV/c^2]	[GeV/c]	[GeV/c]	[GeV/c^2]	[dg.]	[GeV/c^2]
	$>$	$>$	$<$	$<$	[,]
120	20	10(15)	40	115	[80,120]
130	25	10(15)	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]





Expected range: $129 < M_H < 236$ GeV
Observed range: $132 < M_H < 238$ GeV

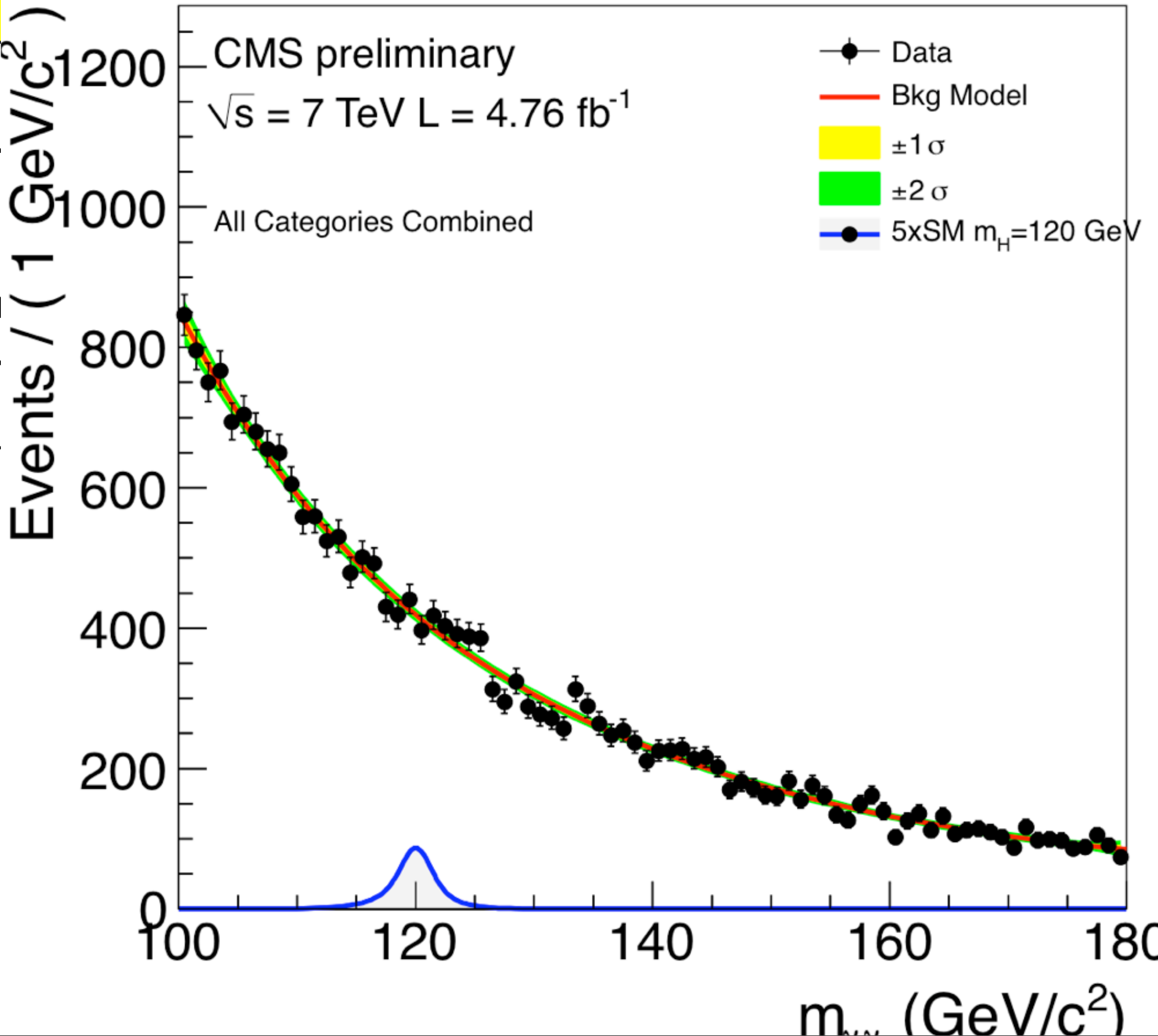
Data describes predicted background well.

$H \to \gamma\gamma$

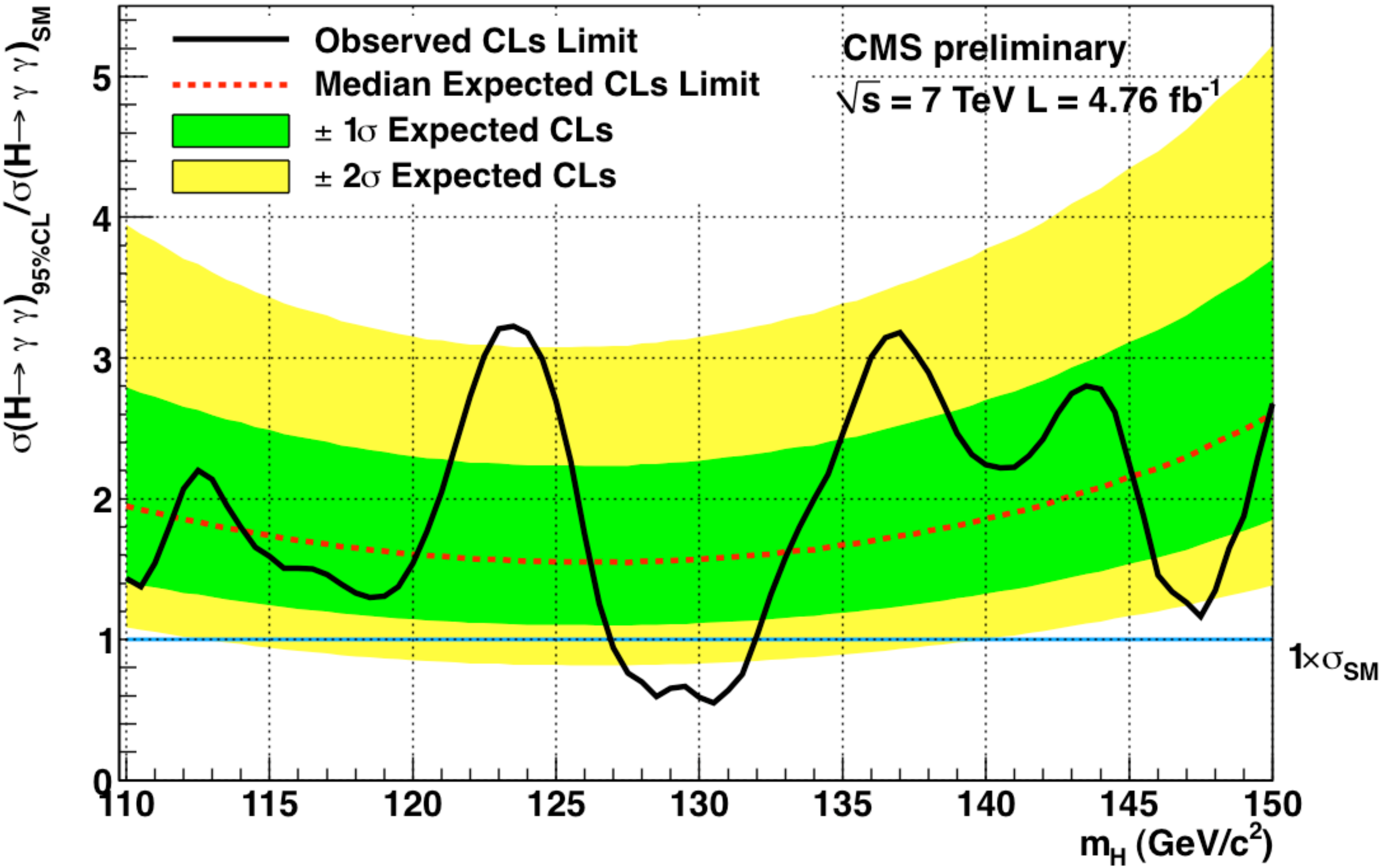
- Low branching ratio but great mass resolution (similar to 4 leptons)
- Useful in the range $110 < M_H < 150 \text{ GeV}$
- requirement: two energetic photons
- signal is an excess over a "smooth" falling background
- Main backgrounds: $pp \to \gamma\gamma \quad ; \quad pp \to \gamma \text{ jet} \quad ; \quad ; pp \to \text{ jet} + \text{jet}$
- Tight photon requirements

$H \rightarrow$

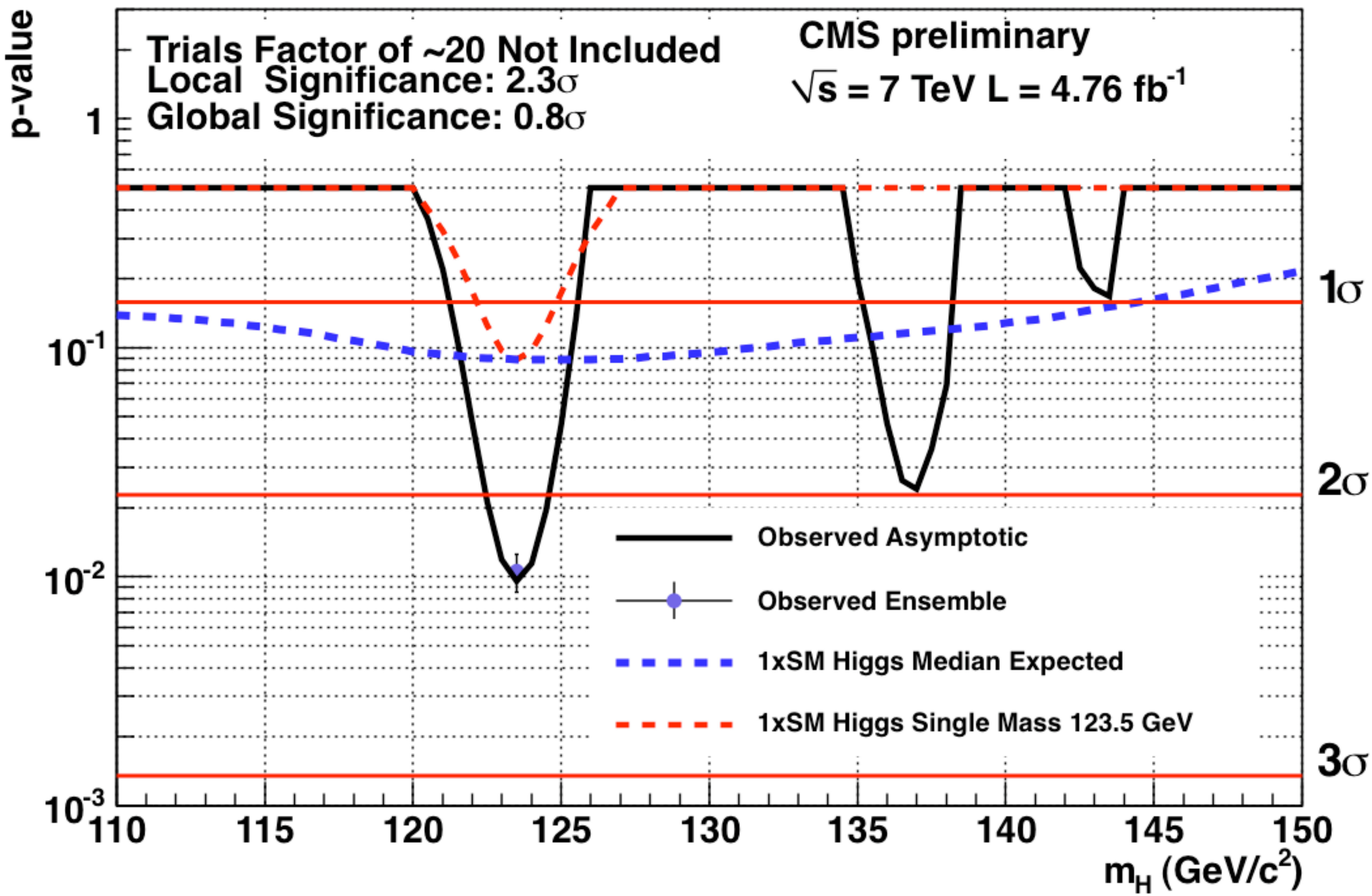
- Low ... ptons)
- Usef
- requ
- signa
- Mair ... $+$ jet
- Tigh



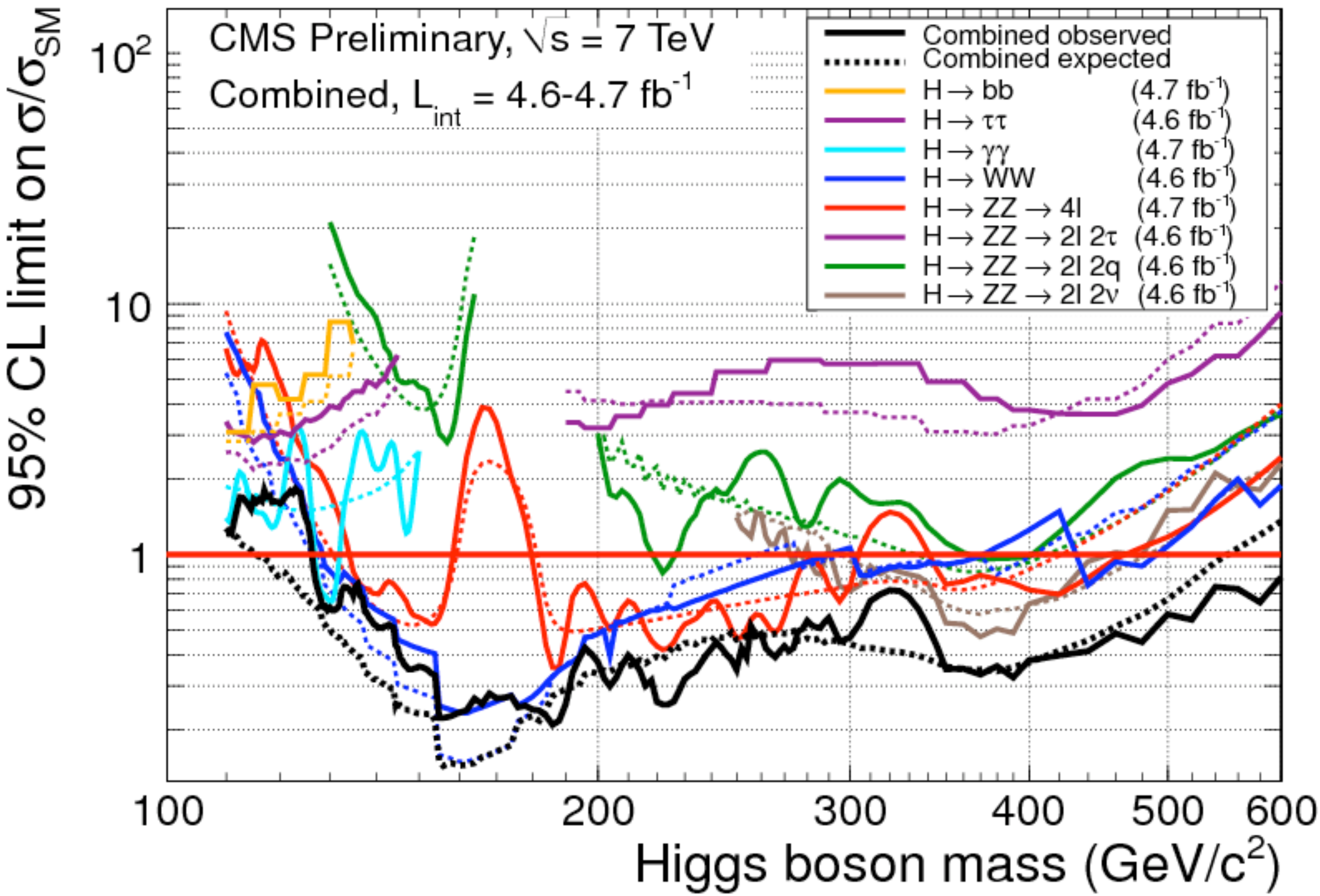
Observed limits



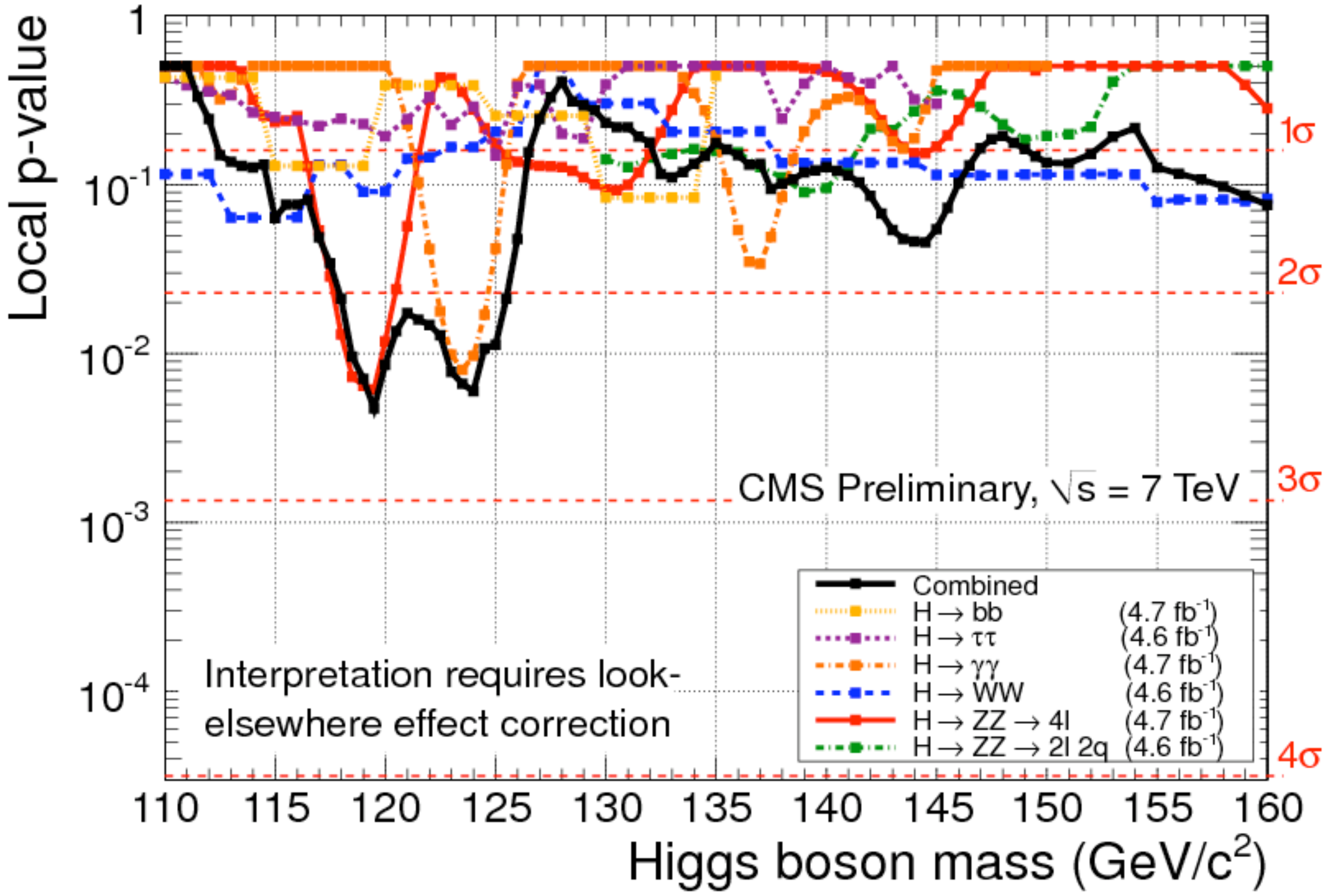
Observed limits



Combining all search channels



Combining all channels



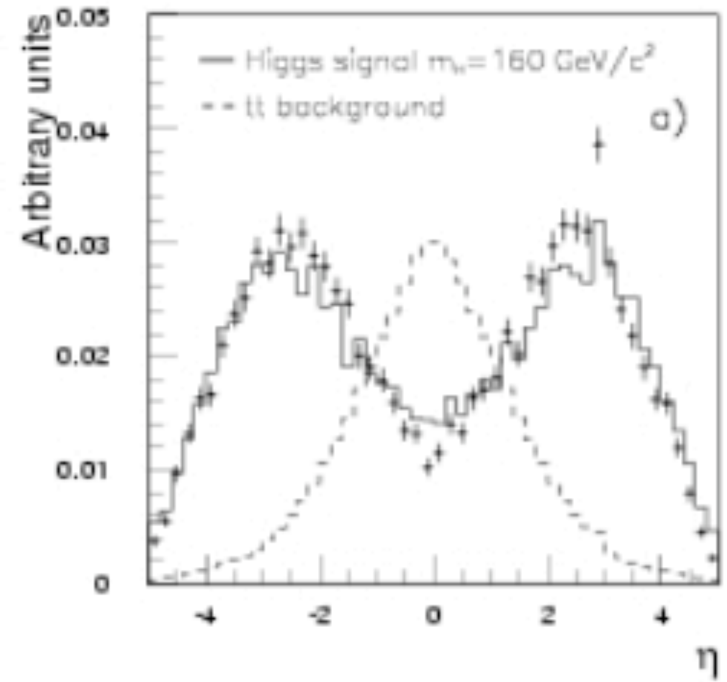
Light Higgs production via WBF (good for 14 TeV)

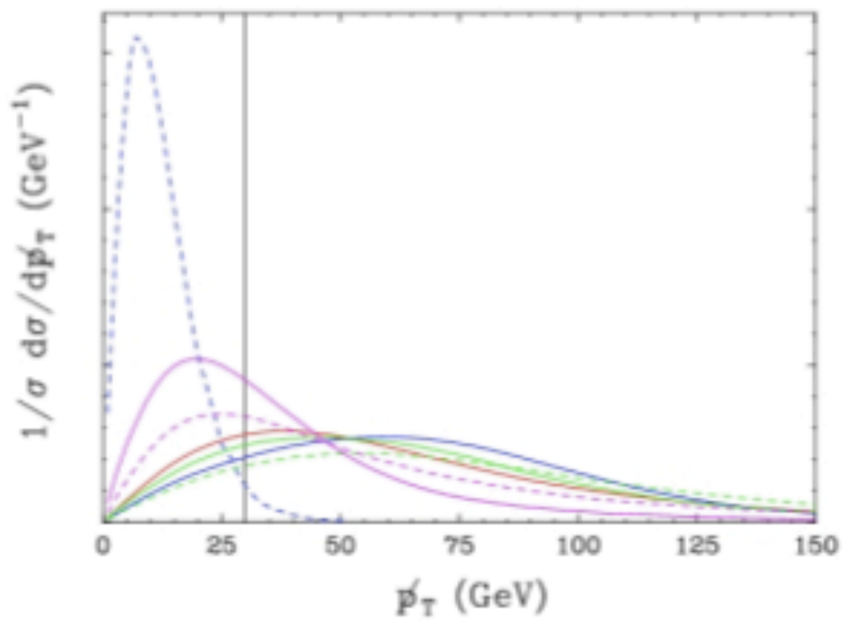
* We can tag the final state jets in $\mathbf{qq} \to \mathbf{Hqq} \to \mathbf{Hjj}$
* Let's focus on $\mathbf{H} \to \tau^+\tau^- \to \mathbf{e}^{\mp}\mu^{\pm}\not{p}_T$
* The main backgrounds are (write the subprocesses)
  - $\mathbf{t\bar{t}} + \mathbf{n}$ jets with $n = 0,\ 1,\ 2$. The extra jet is a tagging jet.
  - $\mathbf{b\bar{b}jj}$ with $\mathbf{b} \to \nu\ell\mathbf{c}$
  - QCD $\tau\tau\mathbf{jj}$ that are higher order of DY $\mathbf{Z} \to \tau\tau$
  - EW $\tau\tau\mathbf{jj}$: WBF of Z's
  - QCD and EW $\mathbf{WWjj}$ production

❇ The main cuts are:

- Rapidity gap and acceptance cuts

$$p_{T_j} \geq 20 \text{ GeV}\,, \quad |\eta_j| \leq 5.0\,, \quad \triangle R_{jj} \geq 0.7\,,$$
$$p_{T_\ell} \geq 10 \text{ GeV}\,, \quad |\eta_\ell| \leq 2.5\,, \quad \triangle R_{j\ell} \geq 0.7\,.$$
$$\triangle R_{e\mu} \geq 0.4\,.$$
$$\eta_{j,min} + 0.7 < \eta_{\ell_{1,2}} < \eta_{j,max} - 0.7\,,$$
$$\eta_{j_1} \cdot \eta_{j_2} < 0$$
$$\triangle\eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4\,,$$





- b–veto:
  $\mathrm{p_{T_b}} > 20$ GeV$\,, \quad \eta_{\mathrm{j,min}} < \eta_{\mathrm{b}} < \eta_{\mathrm{j,max}}\,.$

- Missing transverse momentum $\not{p}_T > 30$ GeV

- $\mathrm{M_{jj}} > 800$ GeV

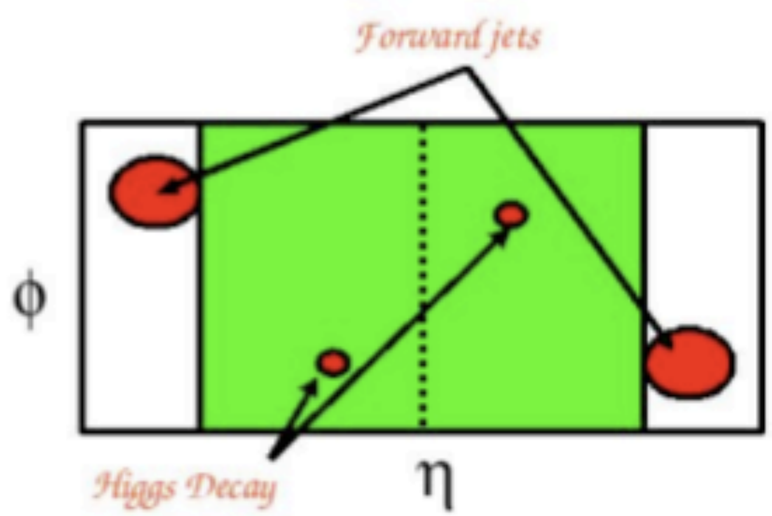
- $\tau\tau$ reconstruction: $\mathbf{M_{\tau\tau} = m_{e\mu}/\sqrt{x_{\tau_1} x_{\tau_2}}}$

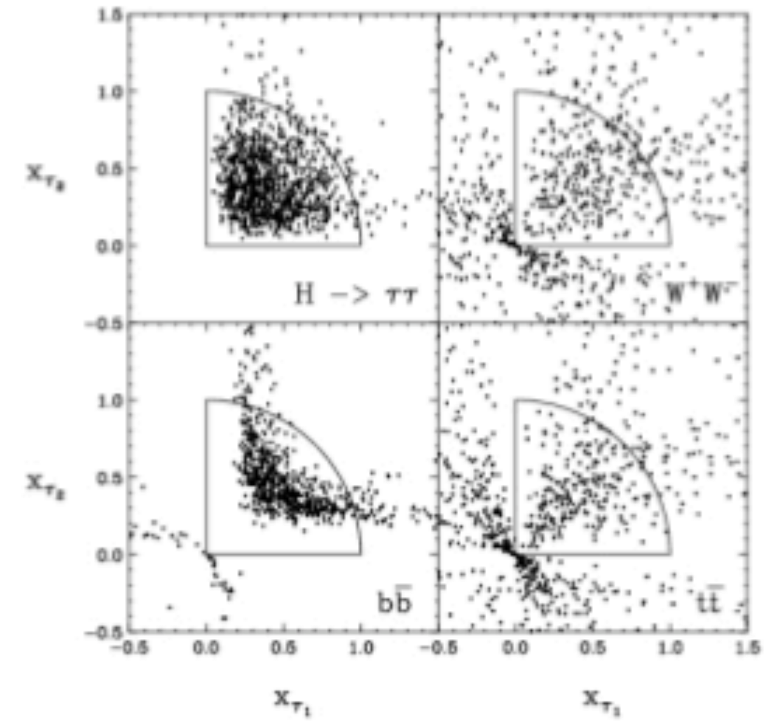
$$\cos\phi_{e\mu} > -0.9 \; .$$
$$x_{\tau_1},\ x_{\tau_2} > 0 \; ,$$
$$x_{\tau_1}^2 + x_{\tau_2}^2 < 1 \; .$$

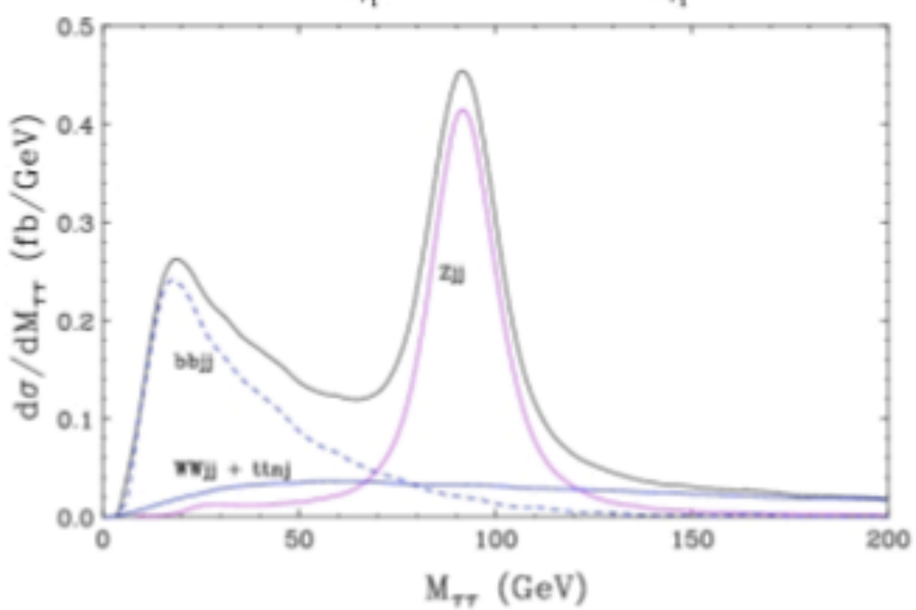
- Lepton correlations: $\triangle \mathbf{R_{e\mu}} < \mathbf{2.6}$

- minijet veto:

$$\mathbf{p_{Tj}^{veto}} > \mathbf{p_{T,veto}} \; ; \; \eta_{\mathbf{j,min}}^{\mathbf{tag}} < \eta_{\mathbf{j}}^{\mathbf{veto}} < \eta_{\mathbf{j,max}}^{\mathbf{tag}}$$







Effect of the cuts for $\mathbf{M_H = 120}$ GeV and a bins $\pm\mathbf{10}$ GeV

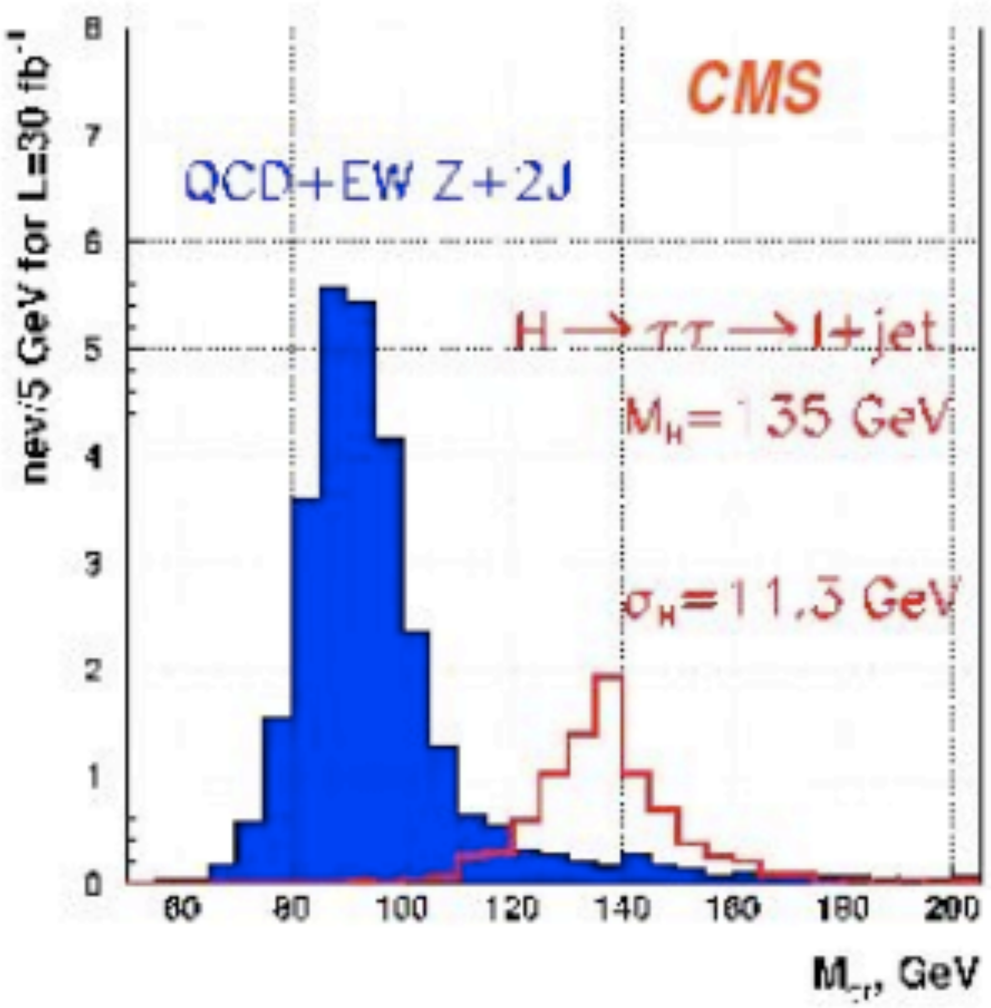
cuts	$H \to \tau\tau$ signal	QCD $\tau\tau jj$	EW $\tau\tau jj$	$t\bar{t} + jets$	$b\bar{b}jj$	QCD $WWjj$	EW $WWjj$	S/B
forward tags	1.34	4.7	0.18	45	8.2	0.18	0.11	1/44
+ b veto				2.6				1/12
+ $\not{p}_T$	1.17	2.3	0.12	2.0	0.28	0.12	0.08	1/4.1
+ M_{jj}	0.92	0.67	0.10	0.53	0.13	0.049	0.073	1/1.7
+ non-τ reject.	0.87	0.58	0.10	0.09	0.10	0.009	0.012	1/1
+ $\triangle R_{e\mu}$	0.84	0.52	0.086	0.087	0.028	0.009	0.011	1.1/1
+ ID effic. ($\times$ *0.67*)	0.56	0.34	0.058	0.058	0.019	0.006	0.008	1.1/1
$P_{surv,20}$	$\times 0.89$	$\times 0.29$	$\times 0.75$	$\times 0.29$	$\times 0.29$	$\times 0.29$	$\times 0.75$	-
+ minijet veto	0.50	0.100	0.043	0.017	0.006	0.002	0.006	2.7/1

Contamination from $\mathbf{H \to WW}$

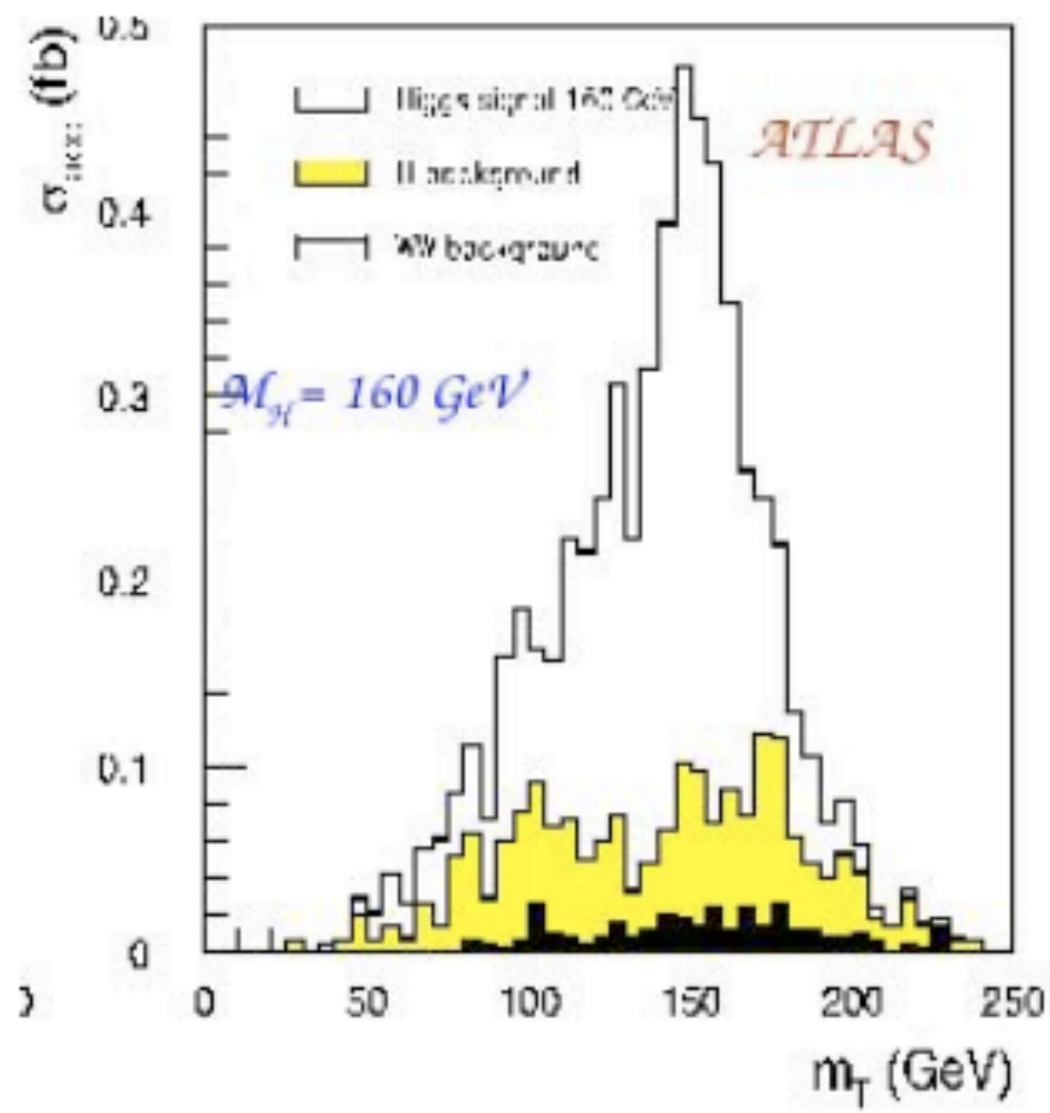
M_H	115	120	125	130	135	140	145	150
B($H \to \tau\tau$)$\cdot\sigma$ (fb)	0.93	0.84	0.74	0.62	0.51	0.39	0.27	0.19
B($H \to WW$)$\cdot\sigma$ (fb)	0.015	0.024	0.034	0.045	0.057	0.067	0.072	0.076

* Even after full simulation the Higgs signal is nice

* $\tau\tau$ channel



* **WW** channel



IV. Top mass measurement

Top mass measurement in $t\bar{t} \to jjb\ (e/\mu)\nu b$ at 14 TeV

- Main background and their size

Process	σ (pb)
signal	250
$bb \to \ell\nu +$ jets	2.2×10^6
$W +$ jets $\to \ell\nu +$ jets	7.8×10^3
$Z +$ jets $\to \ell^+\ell^- +$ jets	7.8×10^3
$WW \to \ell\nu +$ jets	17.1
$WZ \to \ell\nu +$ jets	3.4
$ZZ \to \ell^+\ell^- +$ jets	9.2

- $S/B \simeq 10^{-4}$ This is not as bad as it looks.

✽ Event selection

- 1 isolated $\mathbf{e^{\pm}}$ or $\mu^{\pm}$ with $\mathbf{p_T > 20}$ GeV and $|\eta| < \mathbf{2.5}$
- $\not{E}_T > \mathbf{20}$ GeV .
- 2 tagged $\mathbf{b}$ quarks with $\mathbf{p_T > 40}$ GeV and $|\eta| < \mathbf{2.5}$
- 2 light jets with $\mathbf{p_T > 40}$ GeV and $|\eta| < \mathbf{2.5}$

✽ After cuts $\mathbf{S/B \simeq 78}$

✽ 87k events for 10 fb^{-1}

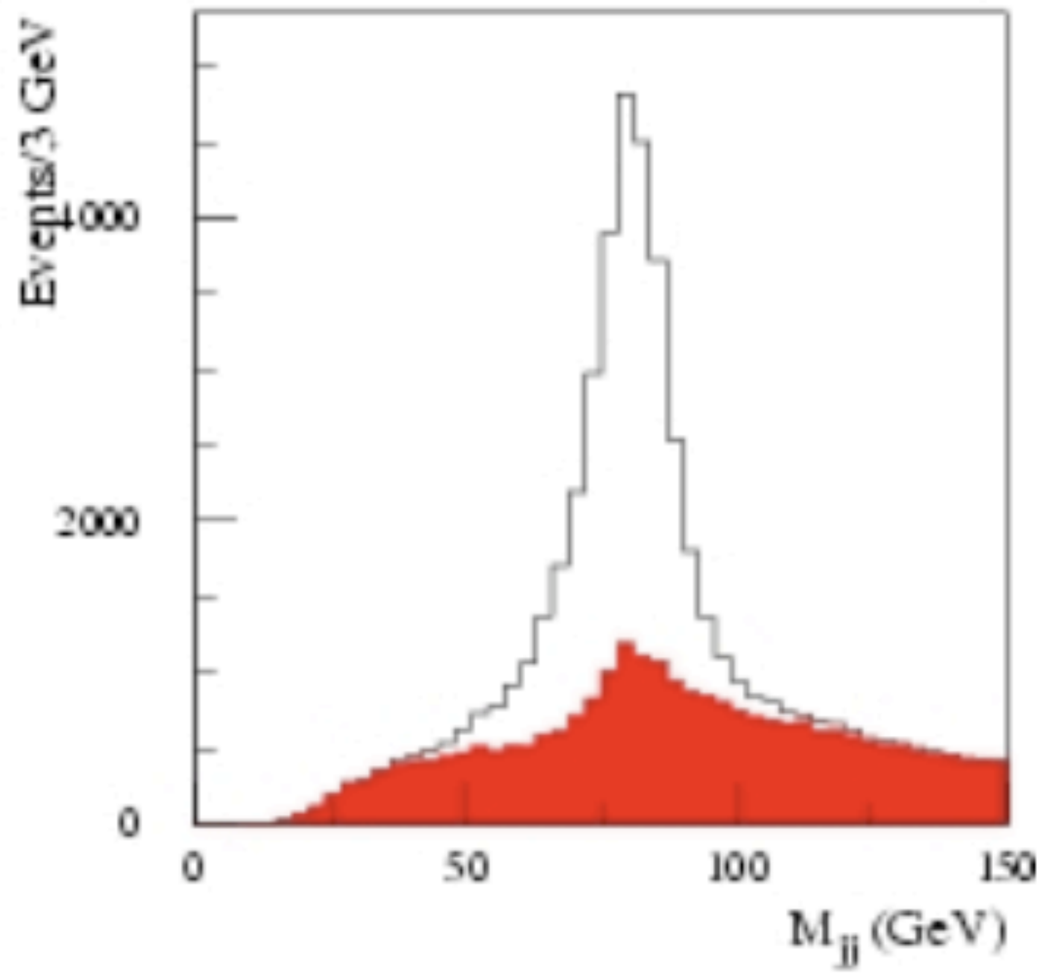
Process	Cross-section (pb)	Total efficiency (%)
$t\bar{t}$ signal	250	3.5
$b\bar{b} \to l\nu + jets$	2.2×10^6	3×10^{-8}
$W + jets \to l\nu + jets$	7.8×10^3	2×10^{-4}
$Z + jets \to l^+l^- + jets$	1.2×10^3	6×10^{-5}
$WW \to l\nu + jets$	17.1	7×10^{-3}
$WZ \to l\nu + jets$	3.4	1×10^{-2}
$ZZ \to l^+l^- + jets$	9.2	3×10^{-3}

✾ Top quark mass from $\mathbf{t \to bjj}$

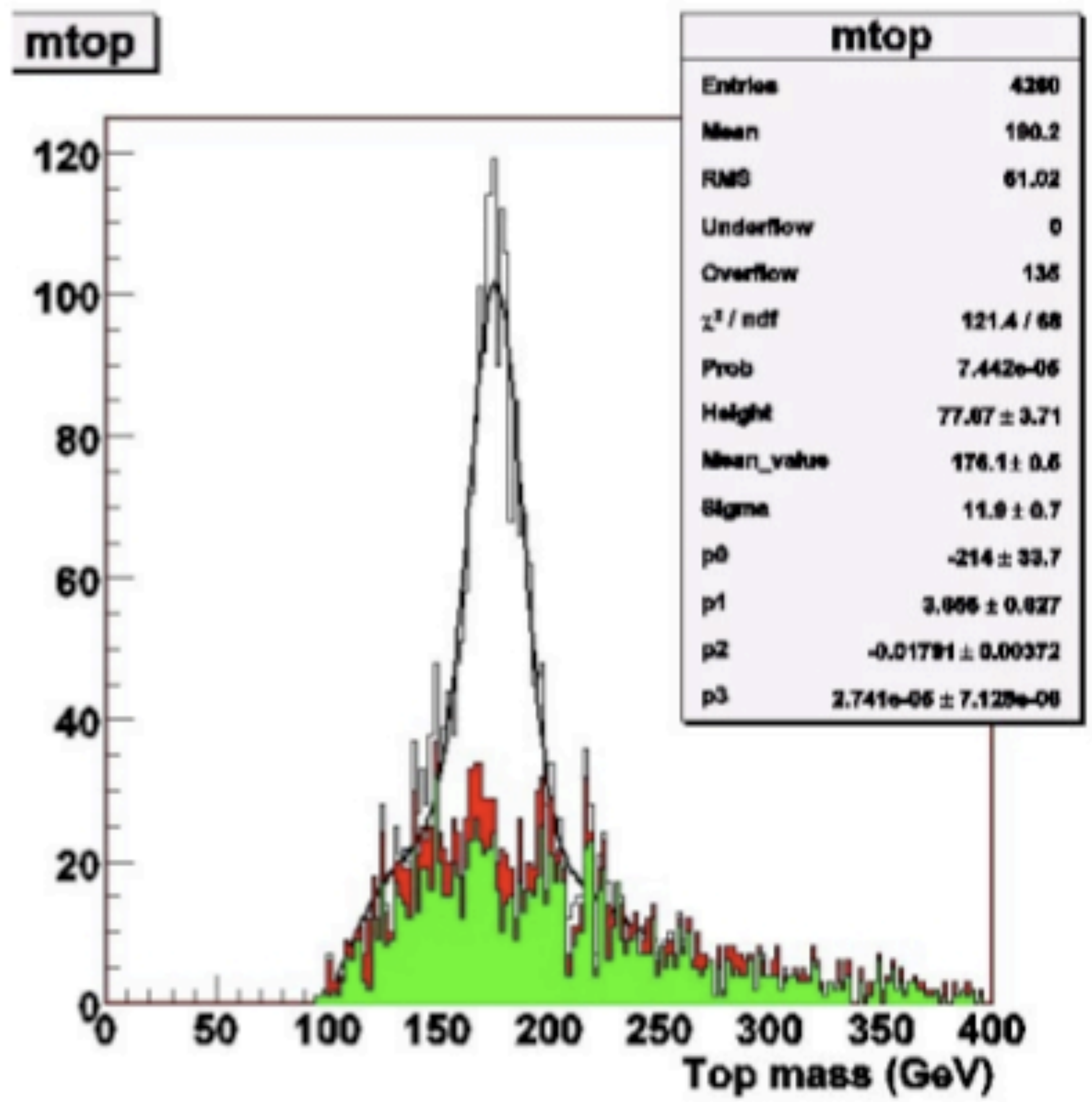
- The event present ≥ 4 jets (ISR and FSR)

- Recontruct the W:
$|\mathbf{M_{jj} - M_W^{PDG}}| < \mathbf{20}$ GeV
(purity 66%)

- choose the b–tagged jet leading to highest $\mathbf{p_T^{top}}$ (81%)



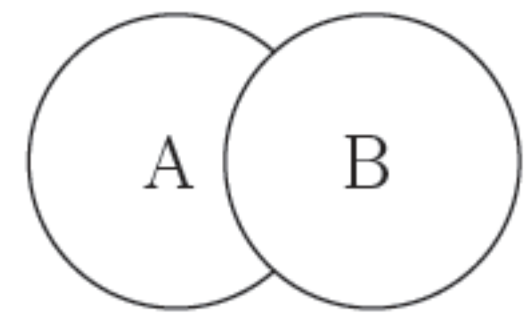
- Possible to measure $\mathrm{M_t}$ with a precision $\simeq 1.3$ GeV (systematic) for 10 fb^{-1}



backup: top mass

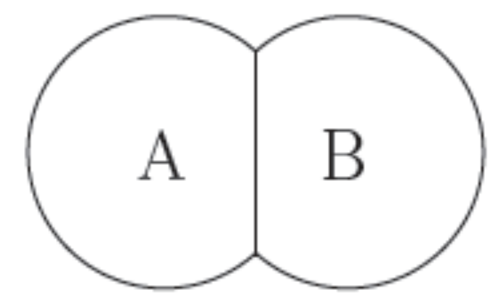
- The different algorithms lead to distinct jets shapes when they overlap

kT (1) starts around softer objects



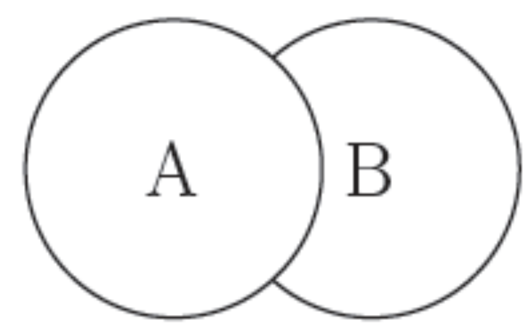
k_T

C/A (0) cares only about distances



C/A

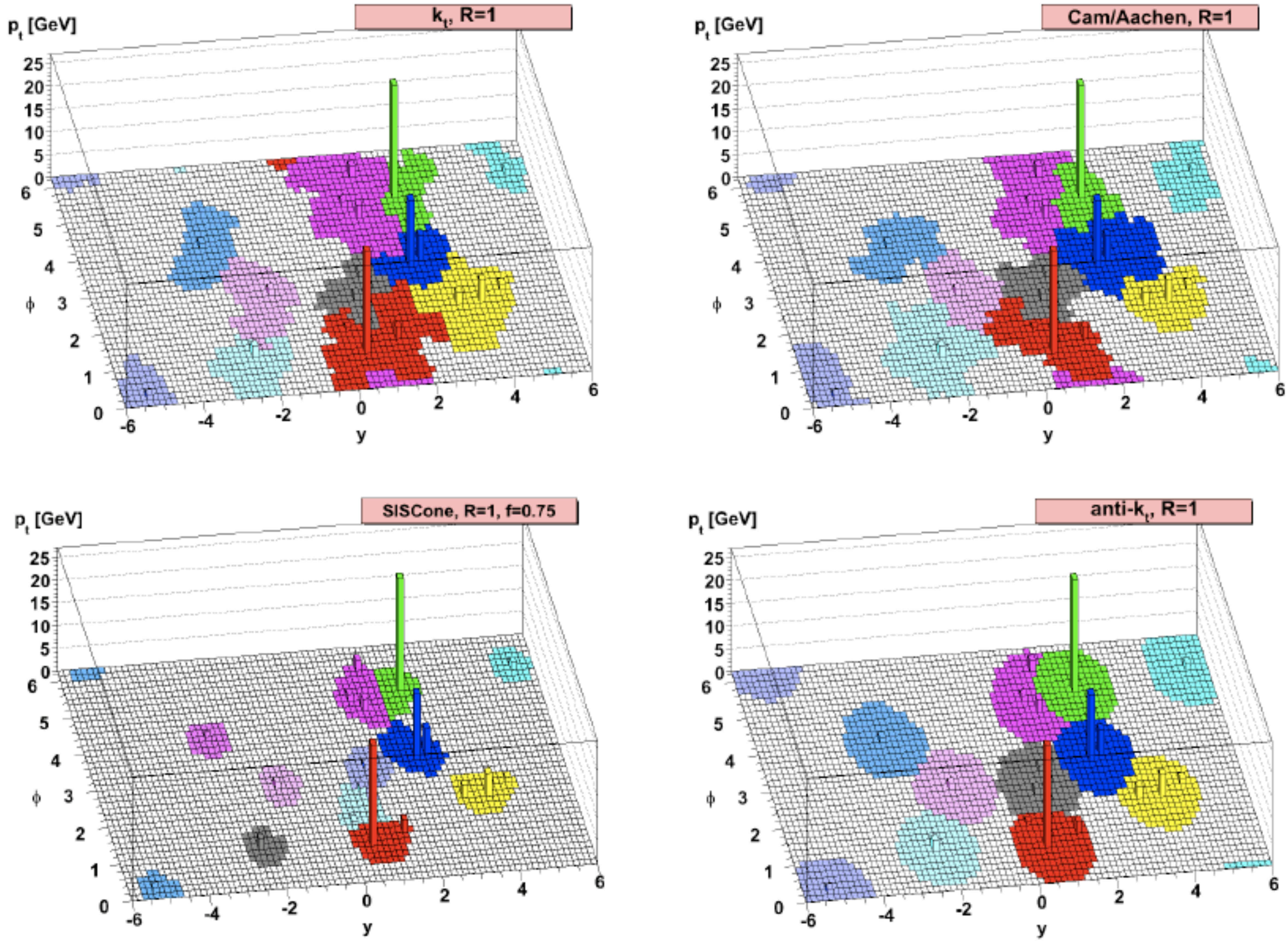
anti-kt (-1) clusters around hard objects



anti$-k_T$

$$p_T^A > p_T^B$$

$$\mathbf{d_{ij}} = \min[\mathbf{p_{Ti}^{2\alpha}}, \mathbf{p_{Ti}^{2\alpha}}] \left(\frac{\mathbf{\Delta R_{ij}}}{\mathbf{R}}\right)^{\mathbf{2}} \quad \text{and} \quad \mathbf{d_{iB}} = \mathbf{p_{Ti}^{2\alpha}}$$



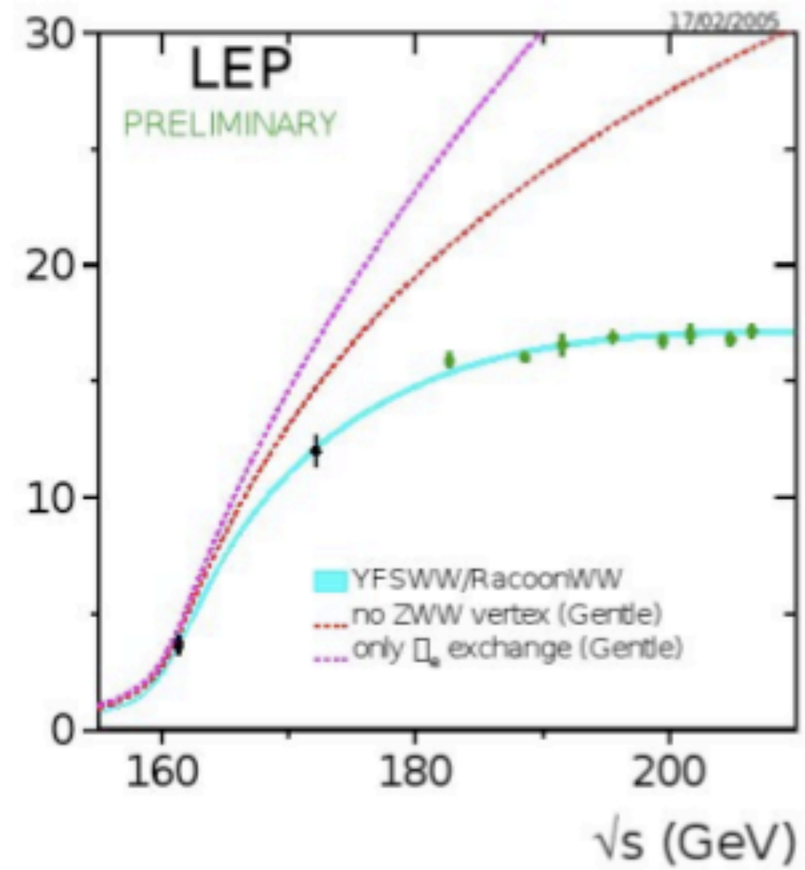
[JHEP04 (2008) 063]

IV. Anomalous couplings

Triple gauge-boson vertices

(hep-ph/0506074)

- ☆ SM gauge fixes TGV
- ☆ We have already observed $\mathbf{W^+W^-}\gamma$ and $\mathbf{W^+W^-Z}$
- ☆ Hypothesis: C and P conservation

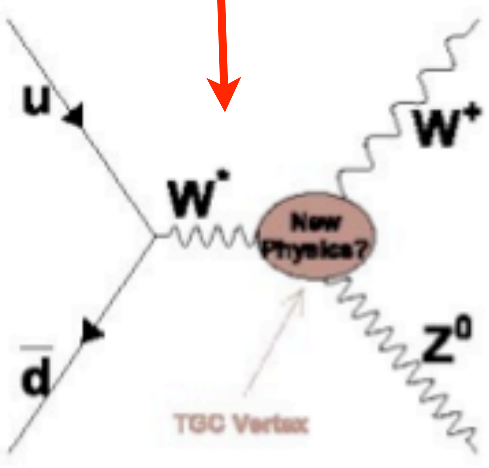


☆ Deviations from SM in terms of 5 new parameters

$$\mathcal{L}_{\rm eff}^{\rm WWV} = -i g_{\rm WWV}\left[g_1^V (W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho \right]$$

analogous to ee->ww

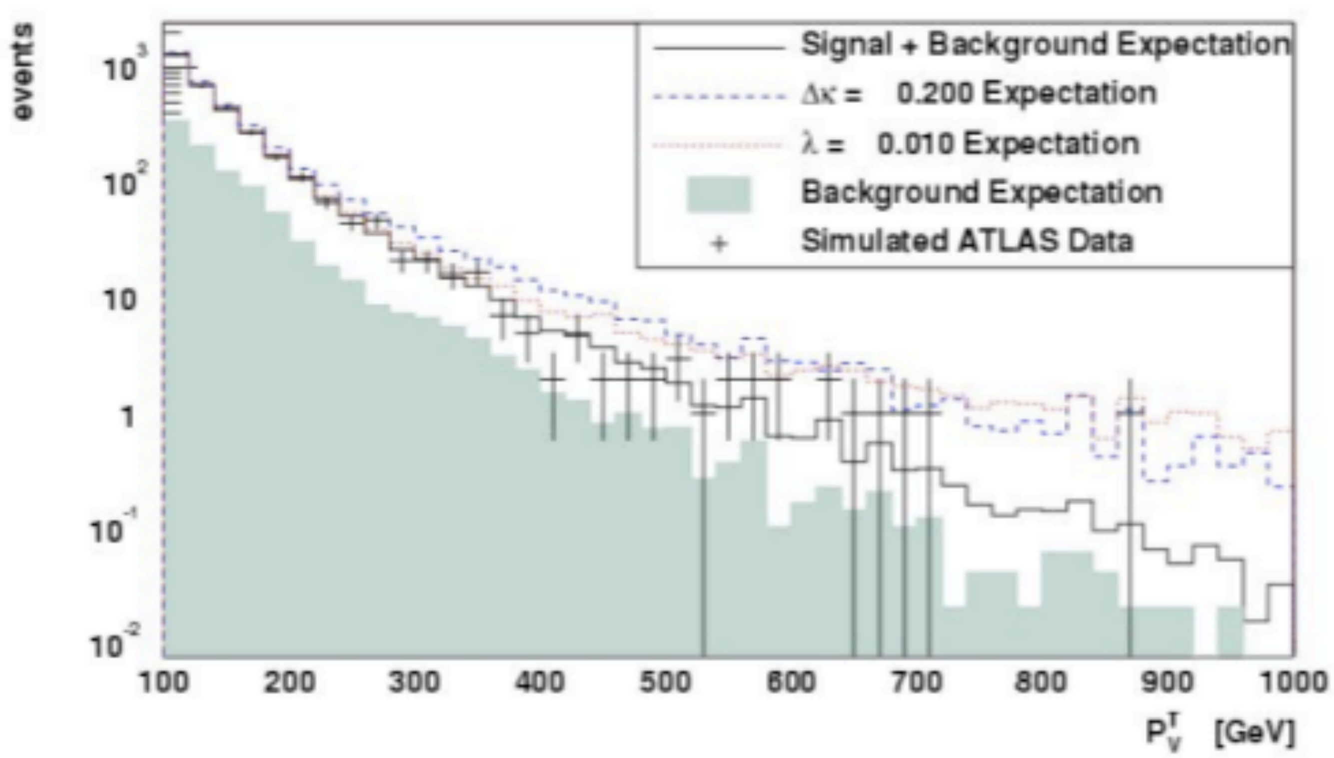
☆ smoking gun: $\hat{\sigma}$ grows with $\sqrt{\hat{s}}$



☆ We must introduce form factors $(1+Q^2/\Lambda^2)^{-n}$

☆ NLO available; uncertainties PDFs

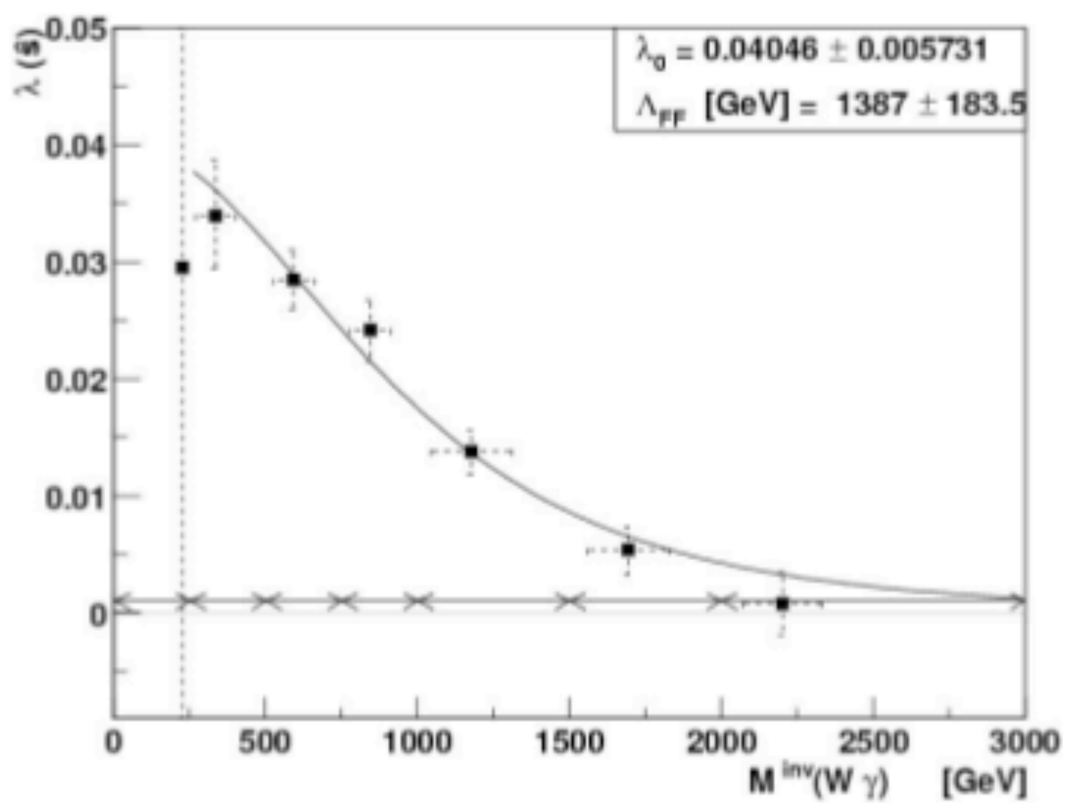
☆ $pp \to W\gamma\ (Z)$: limits fitting p_T^V



☆ Attainable 95% CL limits

anomalous coupling	direct LEP limits	indirect limits	pair production limits at the LHC
$\Delta\kappa_\gamma$	$[-0.105\ ,\ 0.069]$	$[-0.044\ ,\ 0.059]$	$[-0.034\ ,\ 0.034]$
λ_γ	$[-0.059\ ,\ 0.026]$	$[-0.061\ ,\ 0.10]$	$[-0.0014\ ,\ 0.0014]$
g_1^Z	$[-0.051\ ,\ 0.034]$	$[-0.051\ ,\ 0.0092]$	$[-0.0038\ ,\ 0.0038]$
$\Delta\kappa_Z$	$[-0.040\ ,\ 0.046]$	$[-0.050\ ,\ 0.0039]$	$[-0.040\ ,\ 0.040]$
λ_Z	$[-0.059\ ,\ 0.026]$	$[-0.061\ ,\ 0.10]$	$[-0.0028\ ,\ 0.0028]$

☆ The statistics will be enough to measure the form factors:



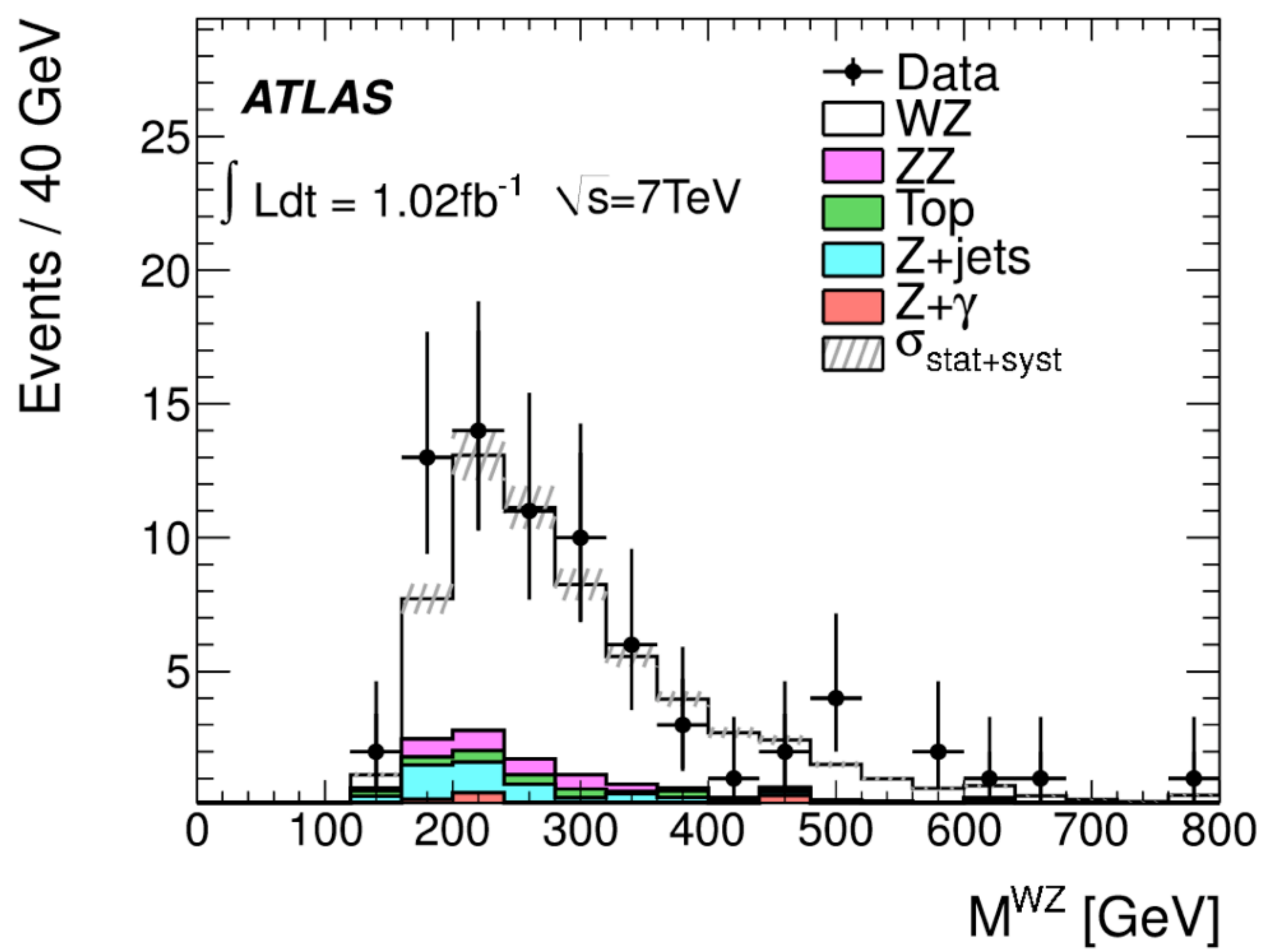
- Presently not enough data have been analyzed at LHC
- ATLAS analyzed 1 fb^{-1} of $WZ \to \ell\ell\ell\not{E}_T$ (71 events)
- basic cuts: $p_T^{\mu,e}(Z) > 15$ GeV; $p_T^{\mu,e}(W) > 20$ GeV;

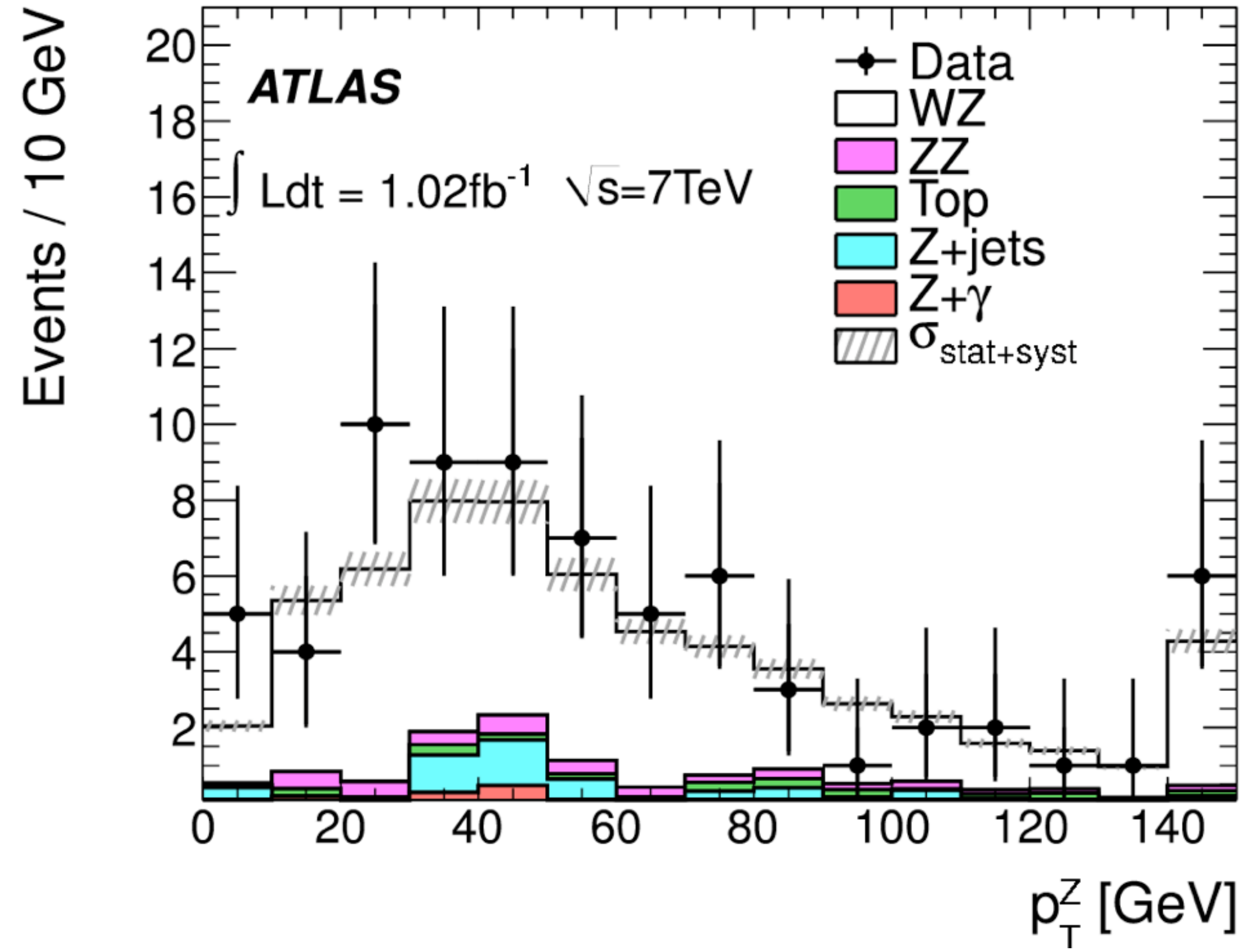
$|\eta_{\mu,e}| < 2.5$; $|m_{\ell\ell} - M_Z| < 10$ GeV;

$\not{E}_T > 25$ GeV; $m_T > 20$ GeV

- Main backgrounds: ZZ, $W/Z+$ jets, $t\bar{t}$, $W/Z+\gamma$

Final State	$eee + E_{\mathrm{T}}^{\mathrm{miss}}$	$ee\mu + E_{\mathrm{T}}^{\mathrm{miss}}$	$e\mu\mu + E_{\mathrm{T}}^{\mathrm{miss}}$	$\mu\mu\mu + E_{\mathrm{T}}^{\mathrm{miss}}$	Combined
Observed	11	9	22	29	71
ZZ	0.4 ± 0.0	1.0 ± 0.1	0.8 ± 0.1	1.7 ± 0.1	$3.9\pm0.1\pm0.2$
W/Z+jets	2.0 ± 0.5	0.7 ± 0.3	1.7 ± 0.5	0.4 ± 0.3	$4.8\pm0.8^{+4.0}_{-1.9}$
Top	0.2 ± 0.1	0.8 ± 0.6	0.9 ± 0.7	0.4 ± 0.5	$2.3\pm1.0\pm0.5$
$W/Z+\gamma$	0.5 ± 0.3	–	0.6 ± 0.4	–	$1.1\pm0.5\pm0.1$
Total Background	3.1 ± 0.6	2.5 ± 0.7	3.9 ± 0.9	2.6 ± 0.6	$12.1\pm1.4^{+4.1}_{-2.0}$
Expected Signal	7.7 ± 0.2	11.6 ± 0.2	12.4 ± 0.2	18.6 ± 0.3	$50.3\pm0.4\pm4.3$



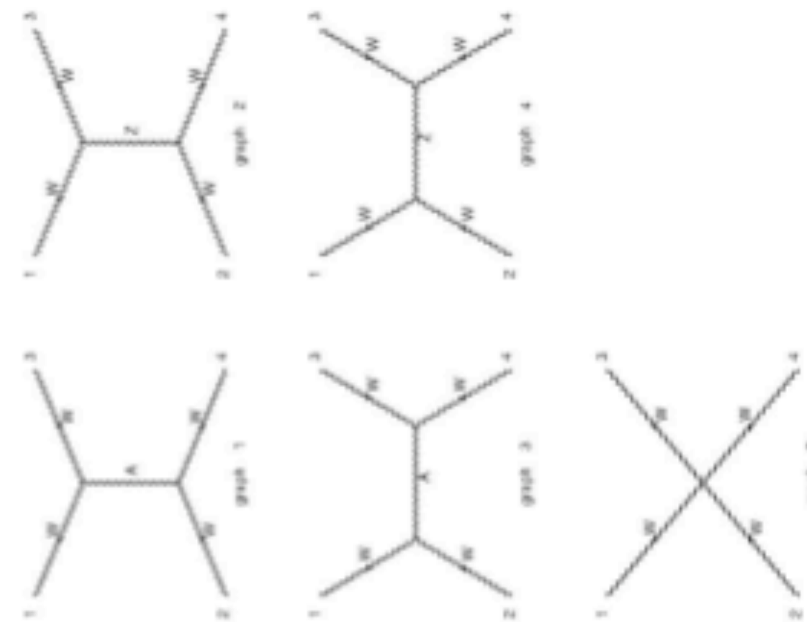


- little statistics to do a fit => use total cross section

Coupling	Observed ($\Lambda = 2$ TeV)	Observed ($\Lambda = \infty$)	Expected ($\Lambda = \infty$)
Δg_1^Z	$[-0.20, 0.30]$	$[-0.16, 0.24]$	$[-0.12, 0.20]$
$\Delta\kappa_Z$	$[-0.9, 1.1]$	$[-0.8, 1.0]$	$[-0.6, 0.8]$
λ_Z	$[-0.17, 0.17]$	$[-0.14, 0.14]$	$[-0.11, 0.11]$

EWSB ×1 TeV scale (Lee, Quigg, Thacker)

- $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$ violates unitarity without EWSB



$$T(s,t) = A\left(\frac{p}{M_W}\right)^4 + B\left(\frac{p}{M_W}\right)^2 + C$$

$A = 0$ without the Higgs.

- Including the Higgs: $a_0 = -\frac{M_H^2}{16\pi v^2}\left[2 + \frac{M_H^2}{s - M_H^2} - \frac{M_H^2}{s}\log\left(1 + \frac{s}{M_H^2}\right)\right]$

- High energy limit: $a_0 \xrightarrow{M_H^2 \ll s} -\frac{M_H^2}{8\pi v^2} \Longrightarrow M_H < 870$ GeV ($M_H < 710$ GeV)

- No Higgs limit: $a_0 \xrightarrow{M_H^2 \gg s} -\frac{s}{32\pi v^2} \Longrightarrow \sqrt{s_c} < 1.2$ TeV

- In the limit $p_g \to 0$

$$\mathcal{M}_1 = \overline{u}(p_q)\frac{\gamma_\alpha \not{p}_q}{(p_q+p_g)^2}\mathcal{N} = \overline{u}(p_q)\frac{2p_{q\alpha}}{2p_q\cdot p_g}\mathcal{N} = \frac{p_{q\alpha}}{p_q\cdot p_g}\mathcal{M}$$

- The total amplitude for gluon emission is this limit is

$$\mathcal{M}_{q\bar{q}g} = \left(\frac{p_{q\alpha}}{p_q\cdot p_g} - \frac{p_{\bar{q}\alpha}}{p_{\bar{q}}\cdot p_g}\right)\mathcal{M}$$

$$|\mathcal{M}|^2_{q\bar{q}g} = 2\frac{p_q\cdot p_{\bar{q}}}{(p_q\cdot p_g)(p_{\bar{q}}\cdot p_g)}|\mathcal{M}|^2.$$

- After including the $d\Phi_3$ we obtain (explain!)

$$\sigma^{q\bar{q}g} = \frac{2\alpha_s}{3\pi}\sigma_{q\bar{q}}\int d\cos\theta_{qg}\frac{dE_g}{E_g}\frac{4}{(1-\cos\theta_{qg})(1+\cos\theta_{qg})}.$$

the quark and antiquark are basically back to back in this limit.