The Dead Cone and Jet substructure

Michele Selvaggi

with F. Maltoni and J. Thaler [1606.03449]

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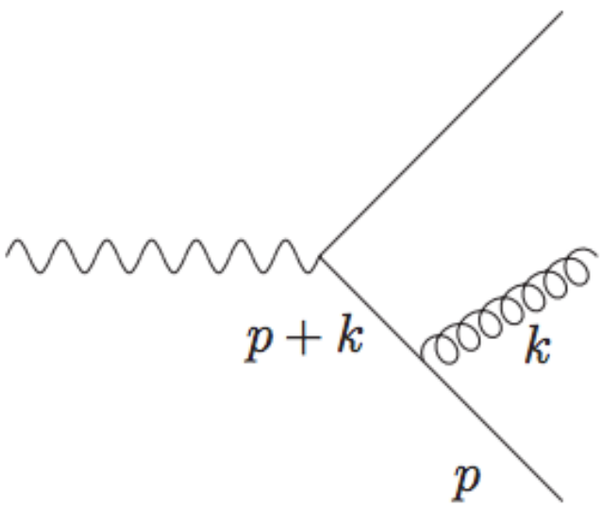
Outline

- The **Dead Cone** effect
- The **Dead Cone** at the **LHC**
- The **Dead Cone** and **Top Tagging**

What is the Dead Cone?

assuming the quark is **stable:**



$$\sim \quad \frac{1}{2p \cdot k}$$

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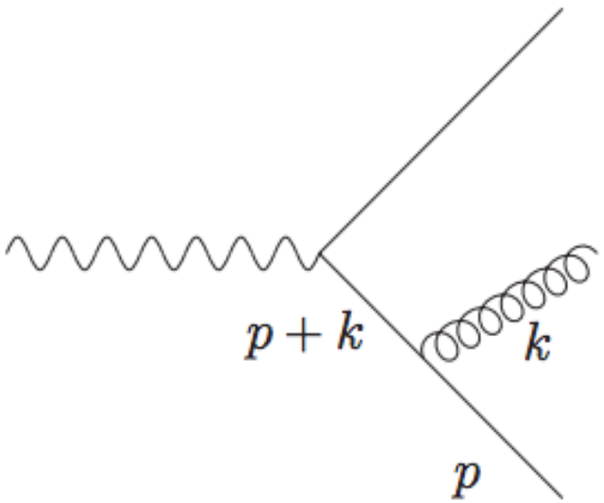

$$\sim \frac{1}{2p \cdot k}$$

m = 0

$$\frac{1}{2E_q E_g (1 - cos\theta_{qg})}$$

soft collinear

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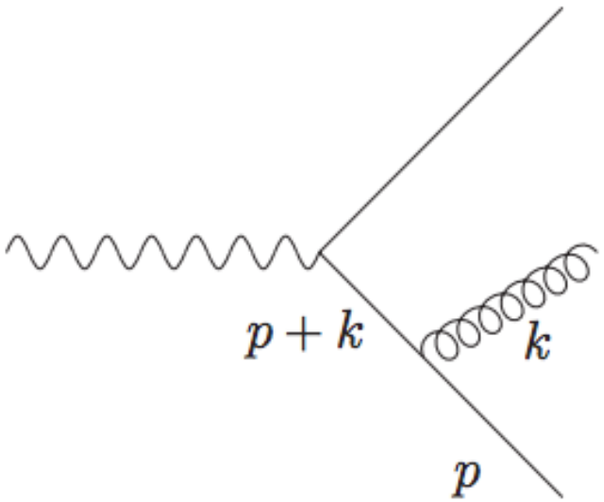

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m = 0

$$\frac{1}{2E_q E_g(1 - cos\theta_{qg})}$$

soft collinear

m ≠ 0

$$\frac{1}{2E_q E_g(1 - v_q cos\theta_{qg})}$$

soft ~~collinear~~

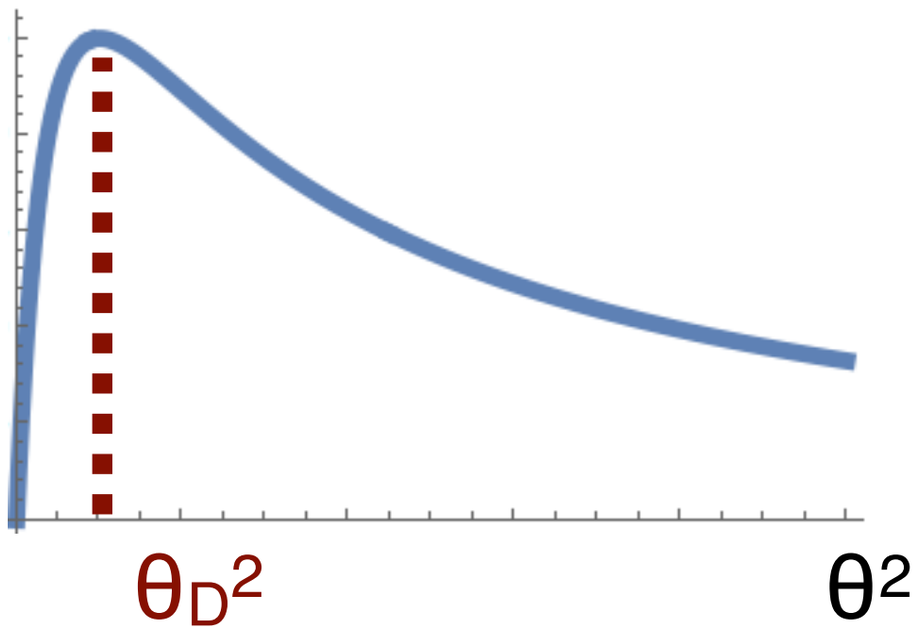
Differential **radiation rate** becomes **finite** at θ ~ 0

What is the Dead Cone?

in **soft** and **collinear** limit :

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}z\,\mathrm{d}\theta^2} \simeq \frac{\alpha_S}{\pi} C_F \frac{1}{z}\frac{\theta^2}{(\theta^2+\theta_D^2)^2} \quad ,$$

$$\theta_D \equiv \frac{m_q}{E_q}$$



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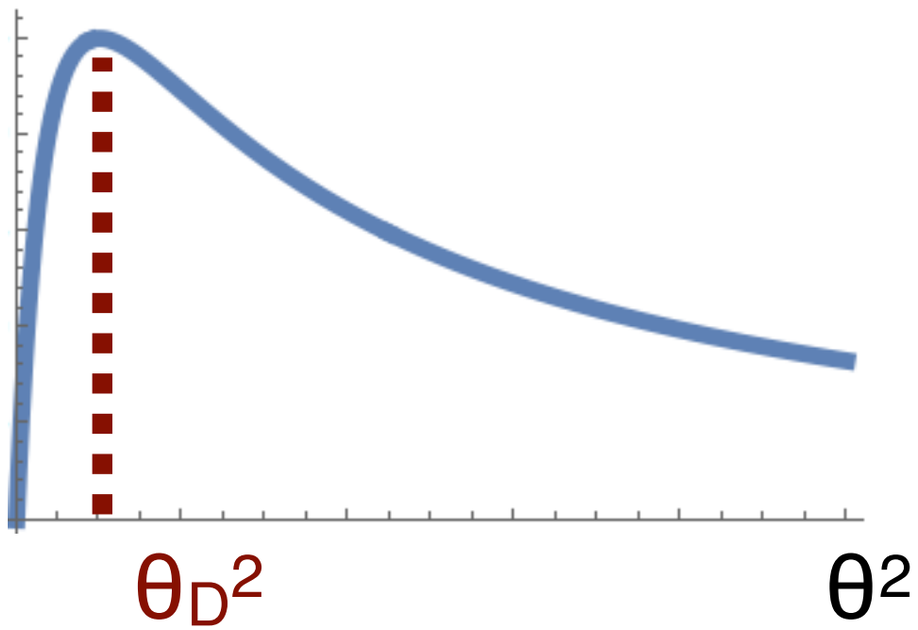
define $\Theta \equiv \dfrac{\theta}{\theta_D}$

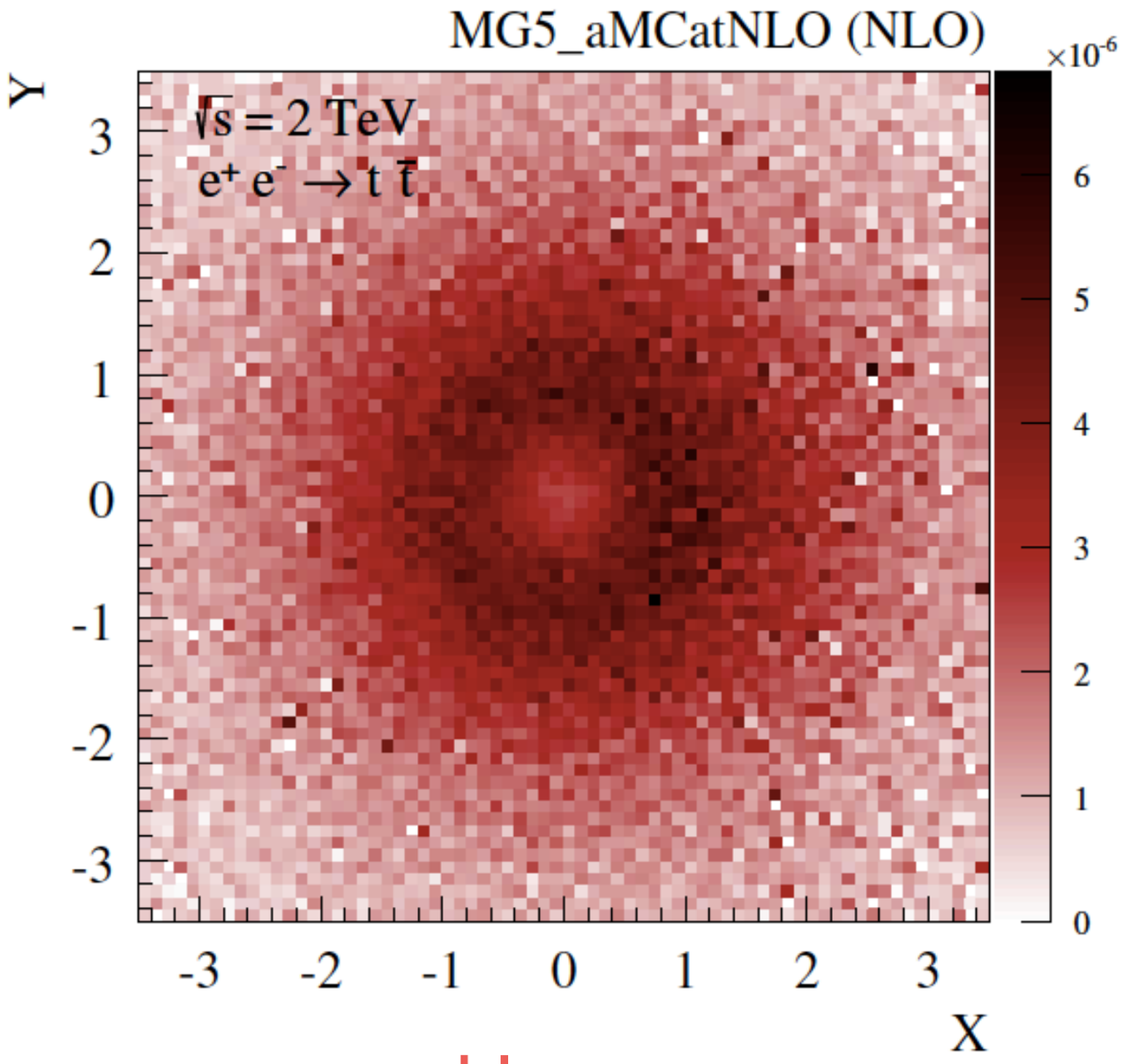
so that **max** is at $\Theta = 1$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Theta^2} \sim \frac{\Theta^2}{(1+\Theta_D^2)^2}$$



What is the Dead Cone?

Does fixed order Monte Carlo correctly reproduce this effect ?



$$X \equiv \Theta \cos\phi$$

$$Y \equiv \Theta \sin\phi$$

stable top

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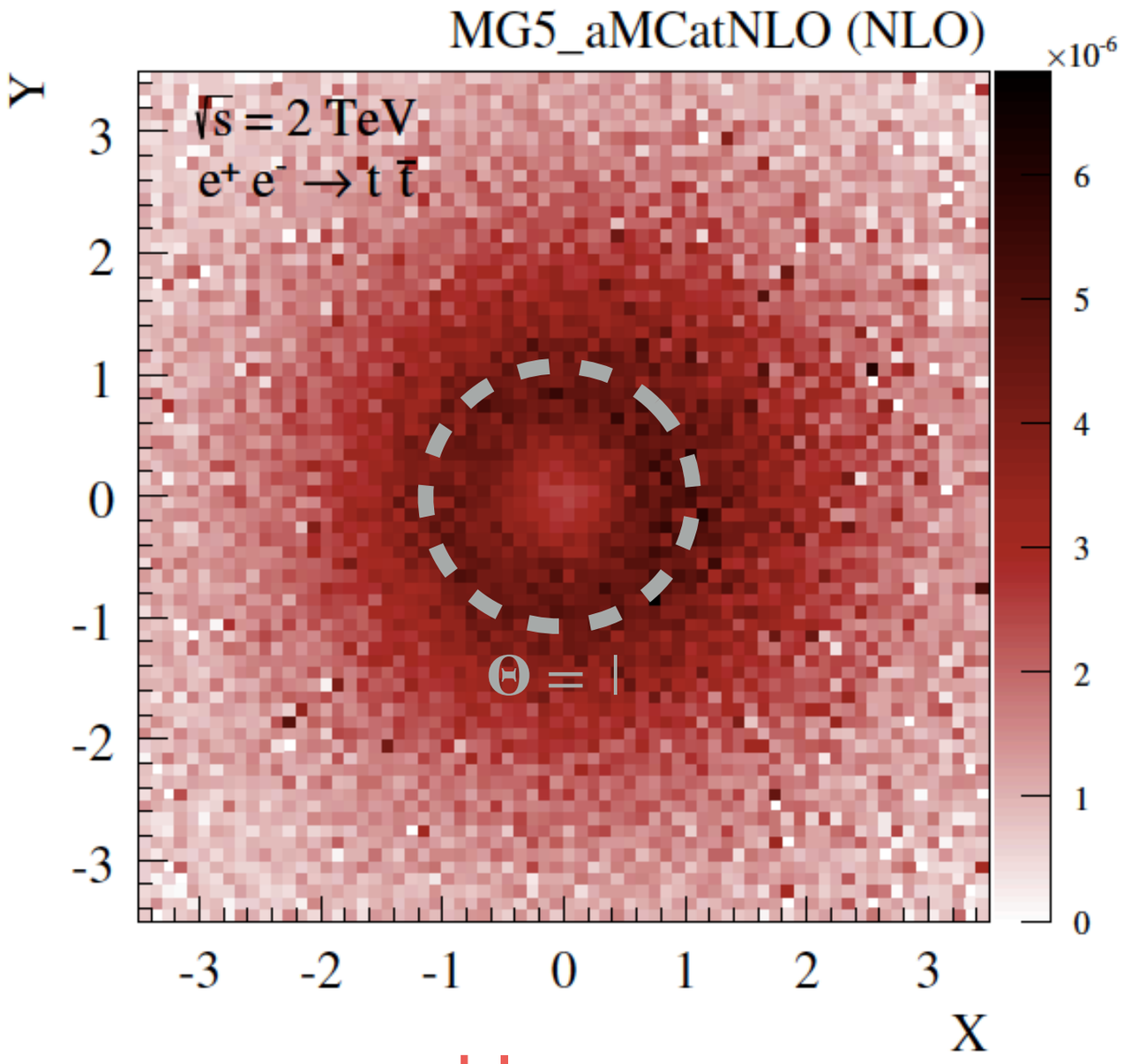

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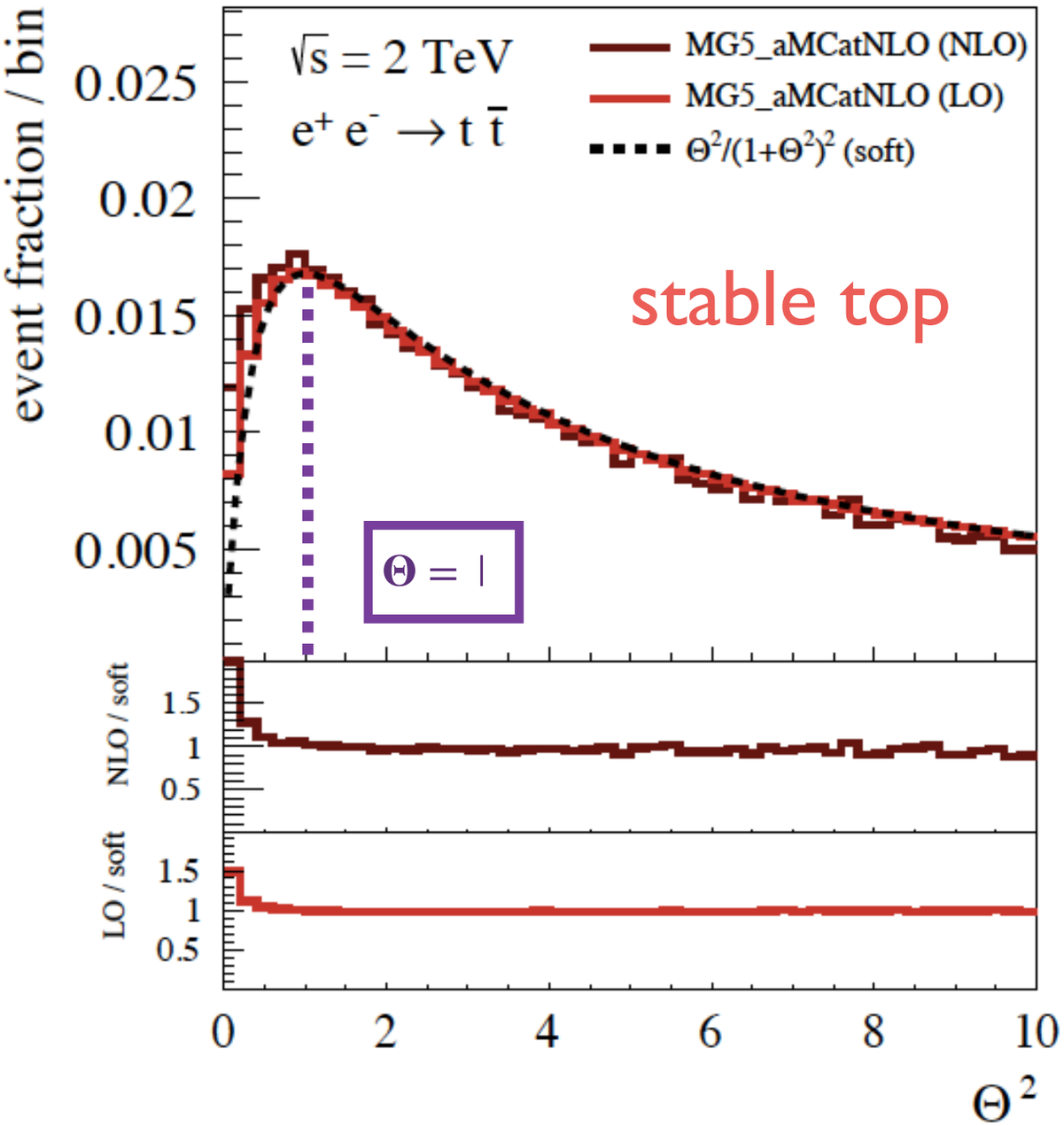
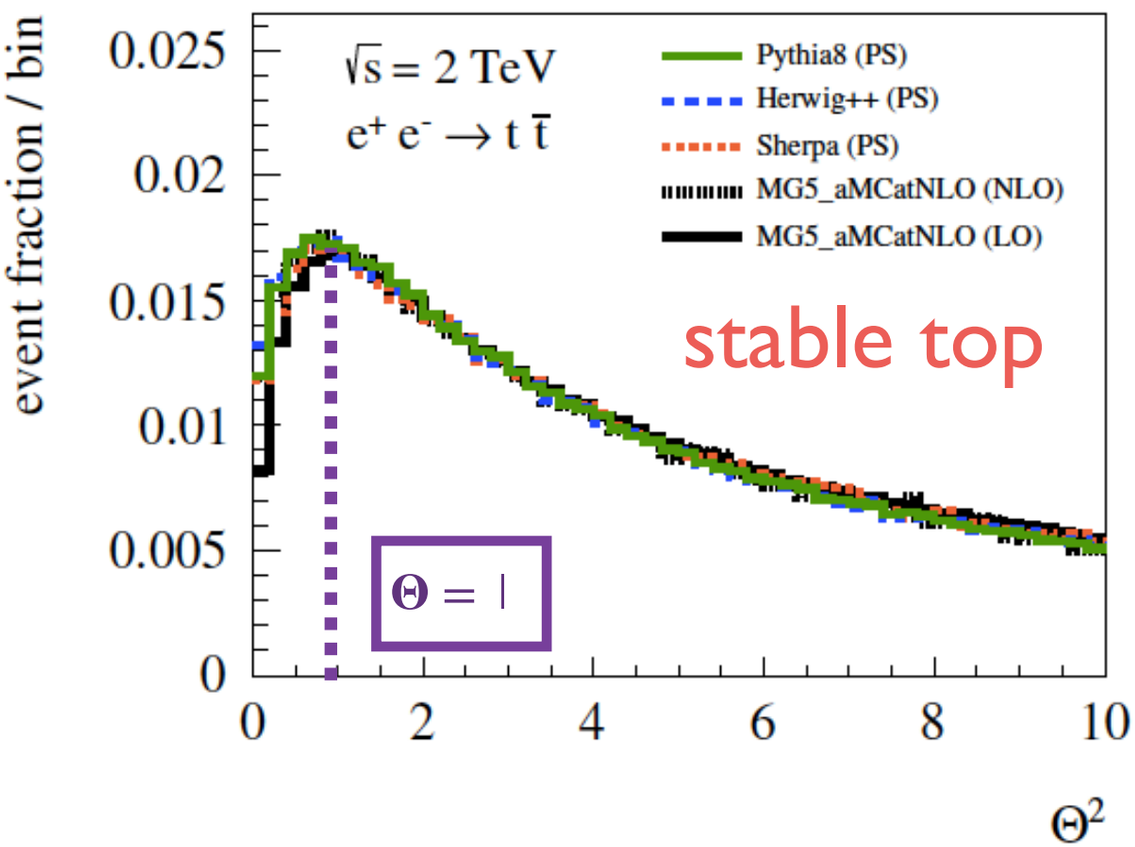
Do fixed order Monte Carlo and PS correctly describe this effect ?

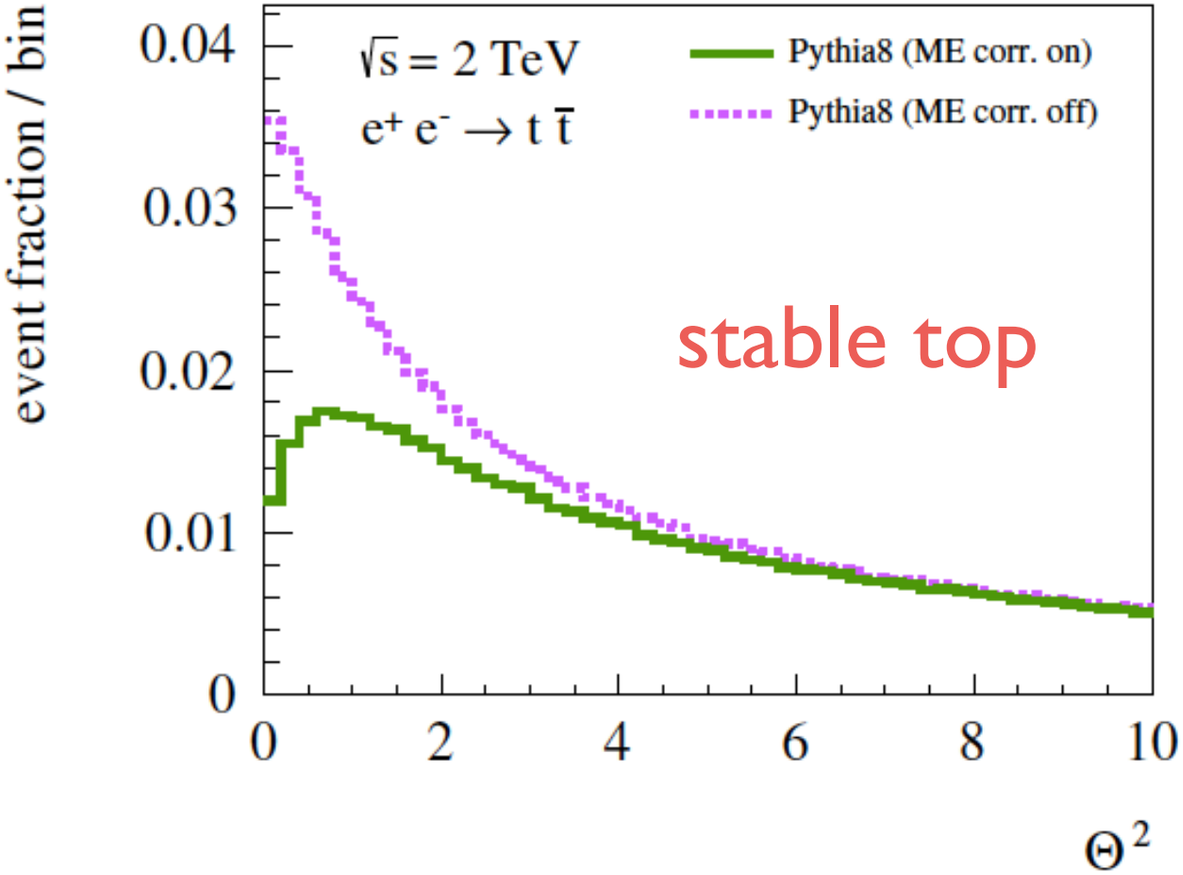


- separate space in 2 semi-sphere
- **sum all gluon** radiation
- 1 entry per event with sum of radiation

What is the Dead Cone?

Do fixed order Monte Carlo and PS correctly describe this effect ? **YES !!**





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TimeShower:MEextended = on/off
TimeShower:recoilDeadCone = on/off

Outline

- The **Dead Cone** effect
- The **Dead Cone** at the **LHC**

The Dead Cone at the LHC

- **Challenging** since **radiation and decay** of massive particle both occur on a similar **angular** scale **$\theta \sim m / E$**
- Which **heavy quarks** are good **candidates** to start with ?
  - **$m_{c,b}$ = 1.5 - 5 GeV** , $p_T = 40$ GeV → **$\theta_D \sim$ 0.03 - 0.1**
    - small angle
    - large backgrounds → **exclusive** decays (e.g. B+ → J/ψ K+) ?
    - which role does **hadronization** play ?

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    - which role does **hadronization** play ?
  - **m_t = 173 GeV** , $p_T = 500$ GeV → **$\theta_D \sim$ 0.3**
    - moderate angle
    - small backgrounds
    - can fully reconstruct **top decay products**

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  - **m_t = 173 GeV** , $p_T = 500$ GeV → **$\theta_D \sim$ 0.3**

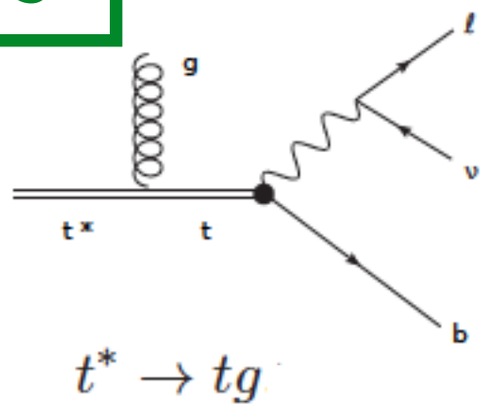
    - moderate angle
    - small backgrounds (radiation in decay being by far the largest)
    - can fully reconstruct **top decay products**

Boosted top quarks are good candidates

Contaminating radiation from decay

Dead cone can be potentially spoiled by **interference** with **radiation in top decay** …

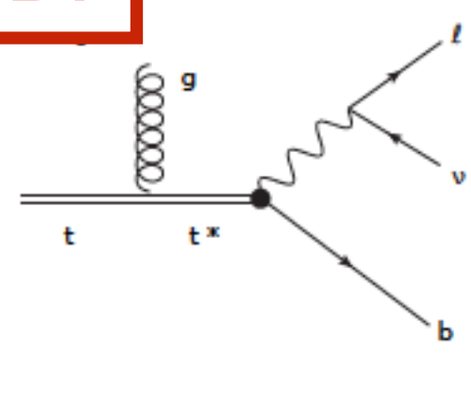
S



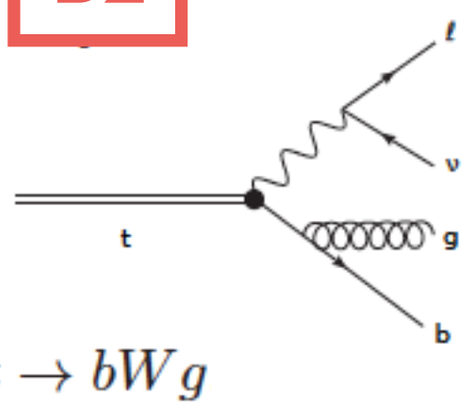
$t^* \to tg$

+

B1



B2



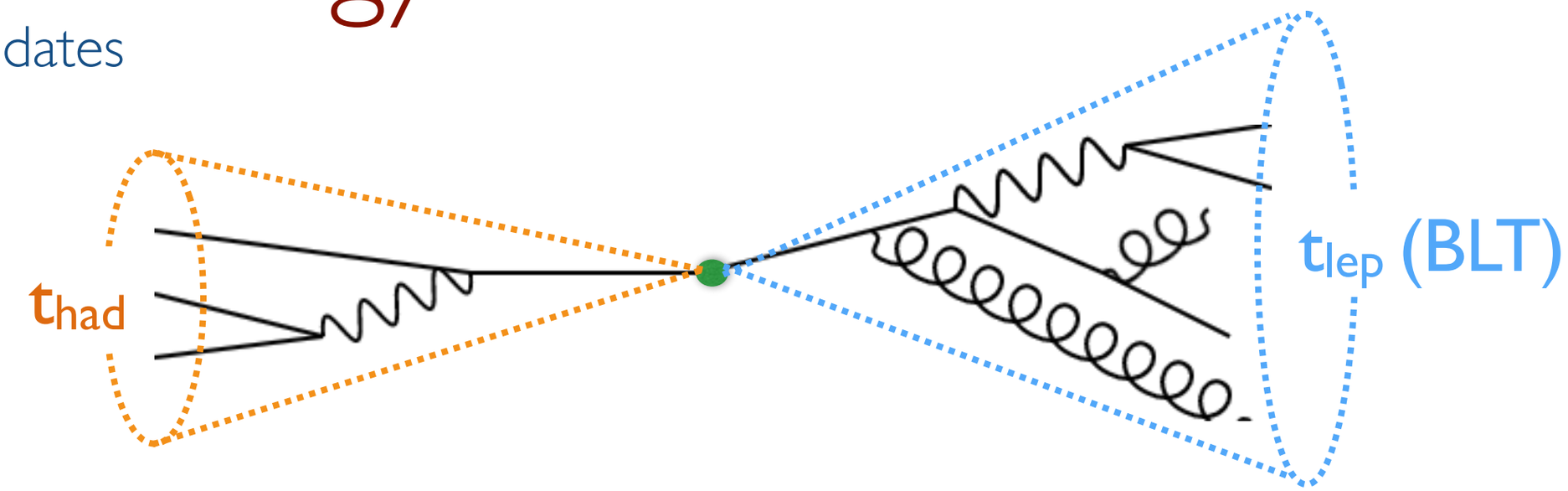
$t \to bWg$

Top width effect becomes **sizable** when : $2p_t \cdot p_g \sim m_t \Gamma_t$

Can **neglect** interference if: $z \equiv \frac{E_g}{E_t} \gg \frac{\Gamma_t}{m_t} \quad \rightarrow \quad z \gtrsim \mathcal{O}(0.1)$

Analysis Strategy

selecting top candidates



- large **top boost** to enhance **FSR rate** ($P \sim \log E_t / m_t$)
- possible **channels**:

  - fully hadronic → **contamination** from **hadronic** W decay
  - fully leptonic → clean, but impossible to accurately reconstruct **top direction**
  - semi-leptonic → **clean, high rate**

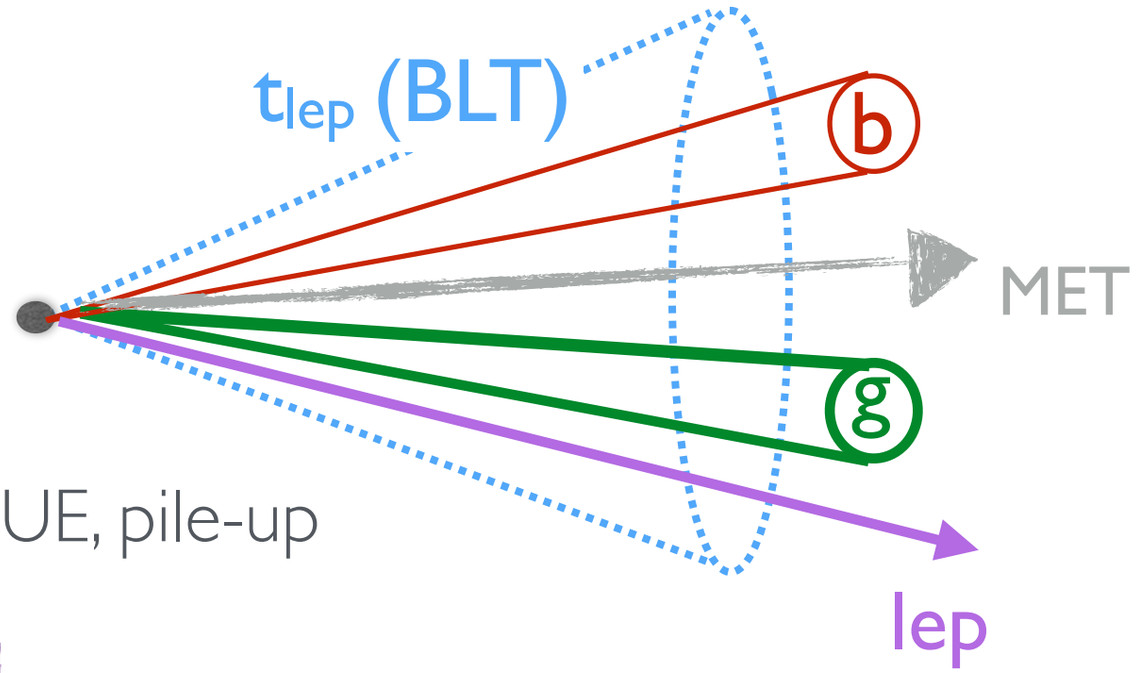
- event **selection**:

  - 2 fat-jets (R=1.0) in central rapidity, $p_T > 300$ GeV
  - 1 fat-jet top-tagged and $p_T > 500$ GeV
  - loosely isolated lepton inside other fat-jet (BLT = "Boosted Leptonic Top")
  - $E_T^{miss} > 50$ GeV

→ **selection designed to ensure close to 100% purity**

Analysis Strategy

find the FSR gluon



- **remove** lepton from fat-jet
- use **Soft Drop** [1402.2657] algorithm to:
  - identify **two hard prongs**
  - get rid off **soft contamination** from ISR, UE, pile-up

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{R_{12}}{R} \right)^{\beta}$$

$$\beta = 0, \qquad z_{\text{cut}} = 0.05.$$

no angular scale is introduced

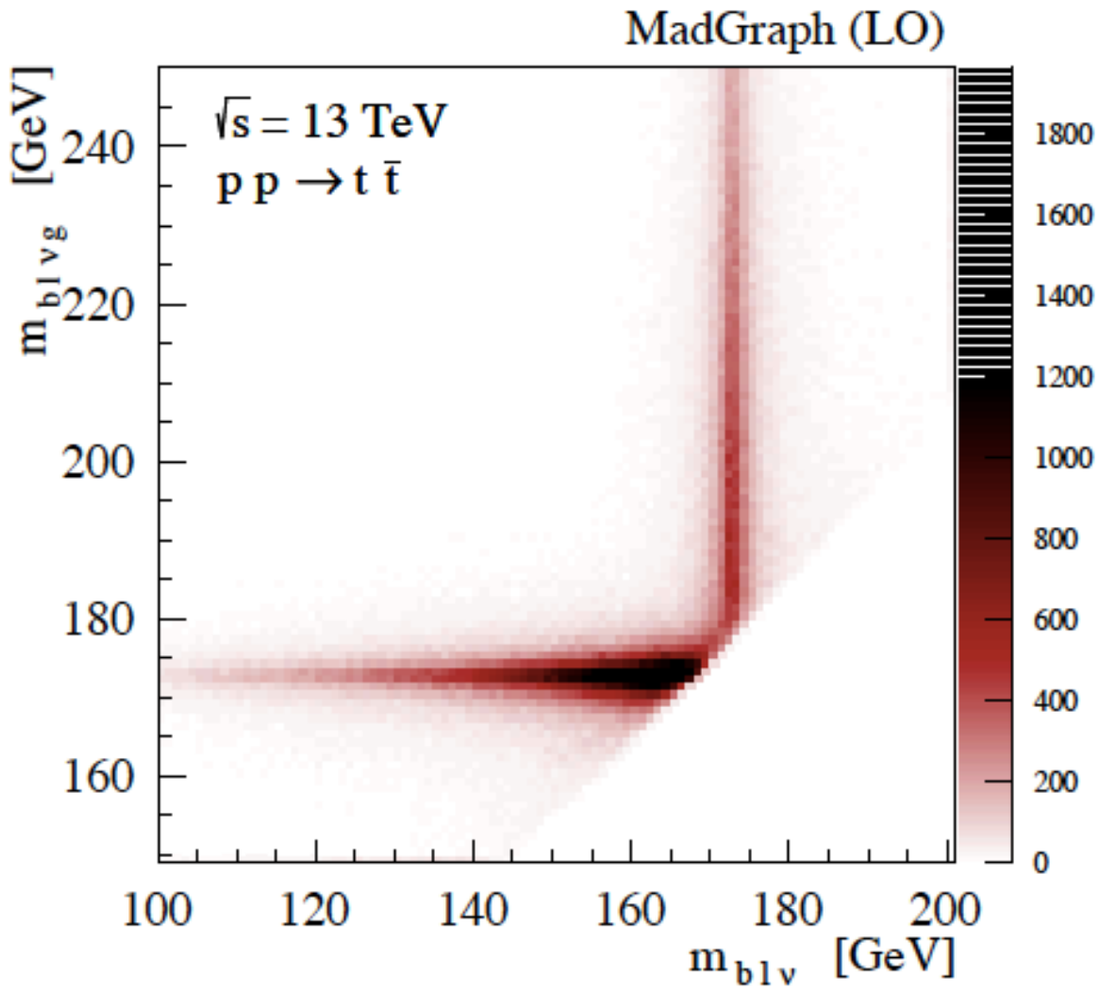
- **discard event** if two prongs not found
- require one **sub-jet** to be **b-tagged**
- the **other sub-jet** is our **gluon candidate**

- in order to reduce contamination from radiation in decay **require:**

$$\frac{p_T^g}{p_T^t} > 0.05.$$

Analysis Strategy

solve for the top direction



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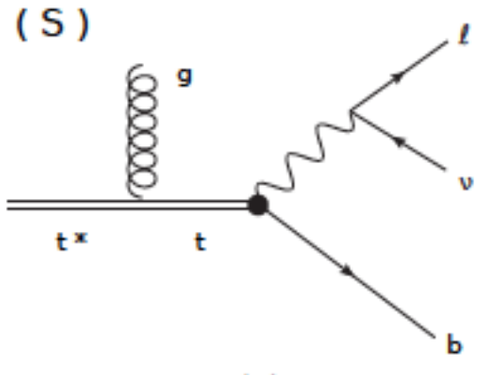

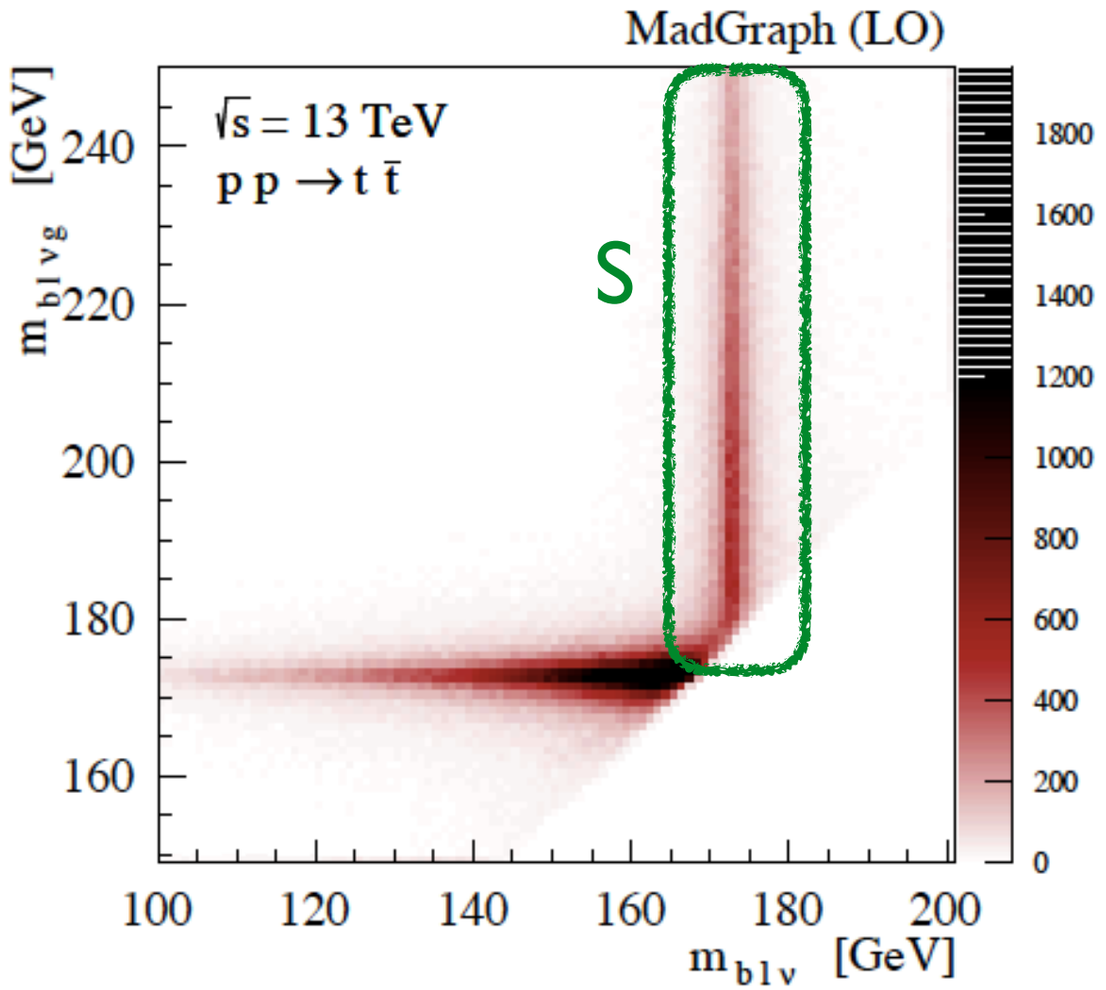

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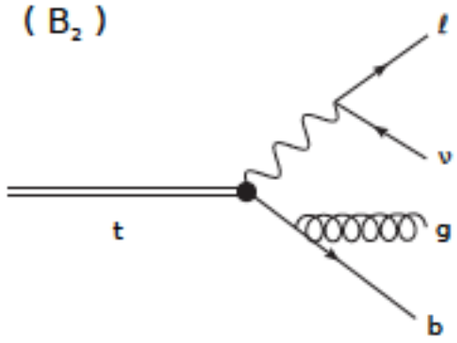
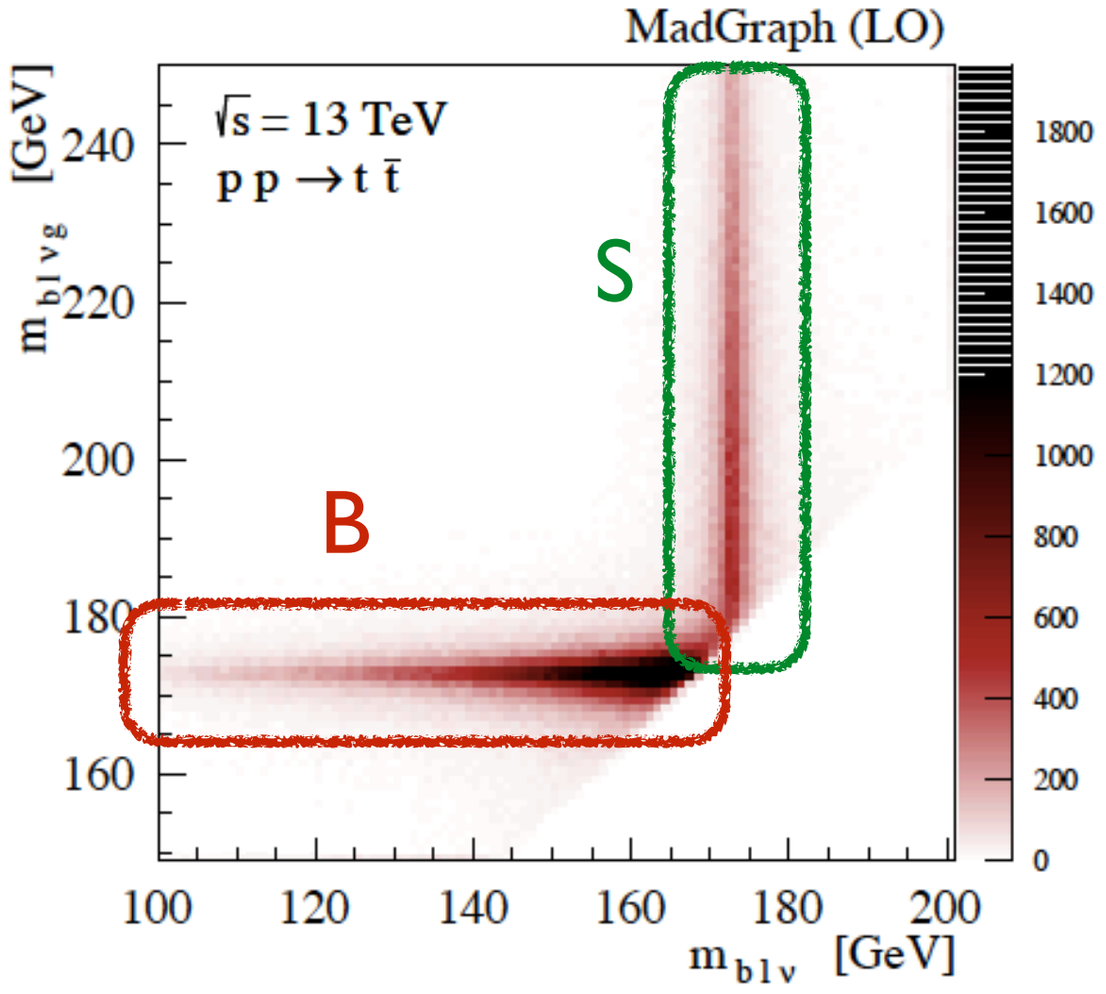




Analysis Strategy

find the FSR gluon

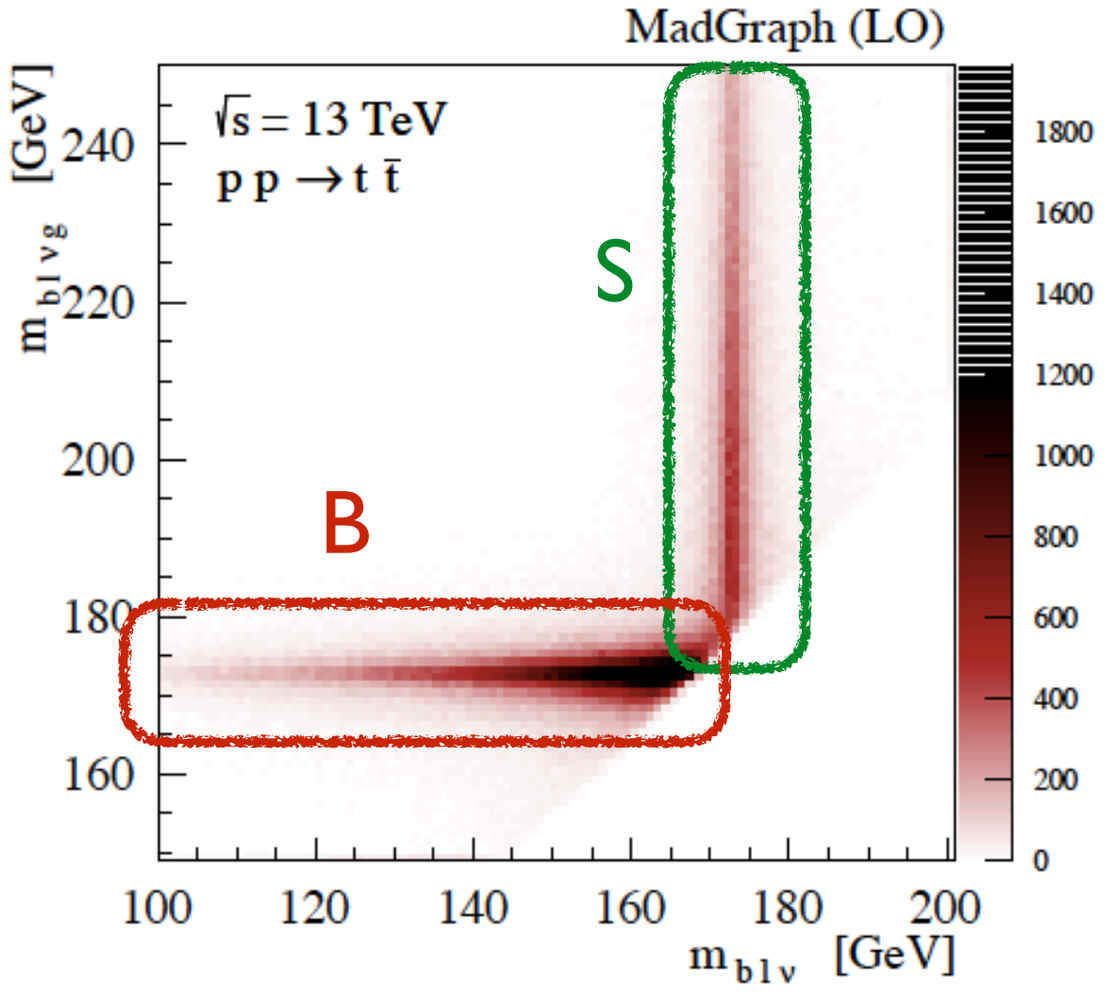
- find the **top direction** by solving for E_z^{miss} :

  - **do not make use of m_{top} constraint**
    otherwise **bias** our background to look like our signal

  - make use of **W mass constraint** (2 solutions)

  - solve **degeneracy** by checking consistency with hypothesis:

    - radiation in production (**S**)
    - radiation in decay radiation (**B**)

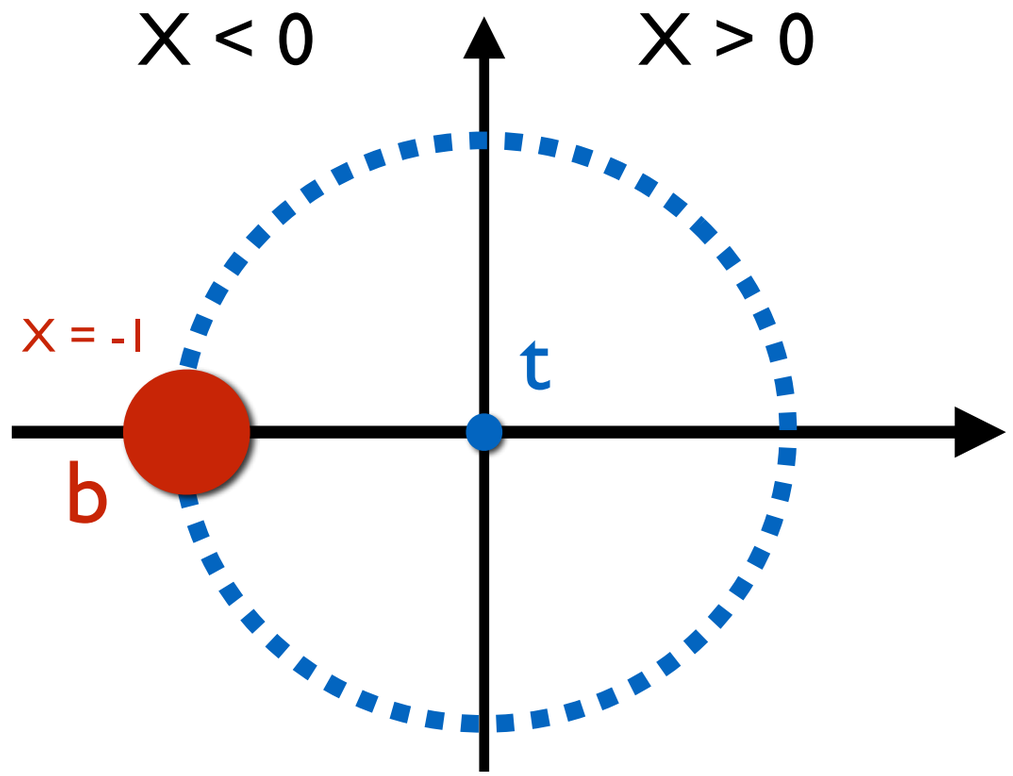


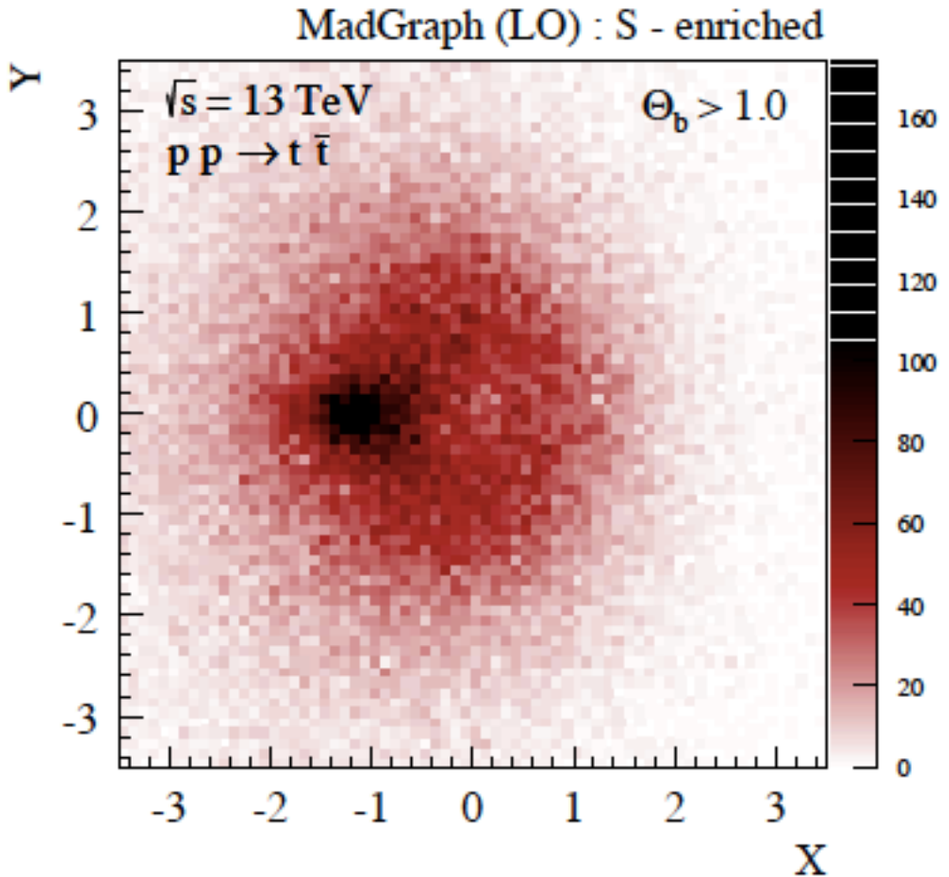
Observing the Dead Cone

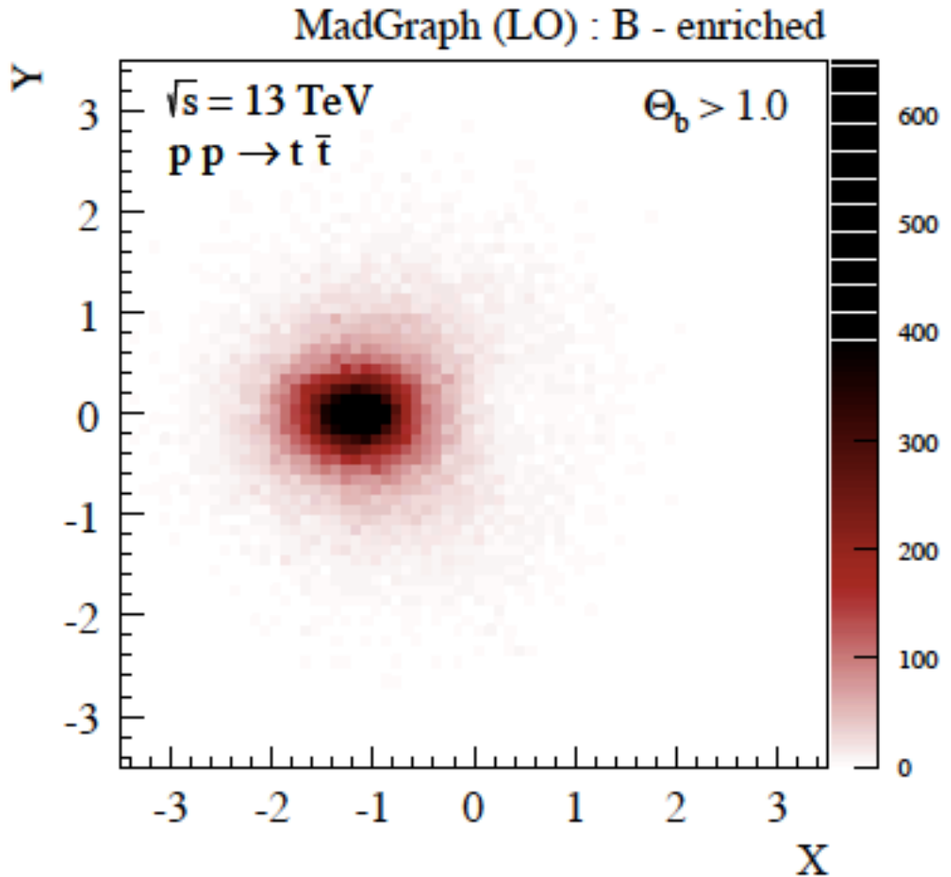
- purity can be increased by "pushing the b-quark away"

  → require **larger angle** between t and b:

$$\Theta_b > 1.0$$







Sensitivity at the LHC

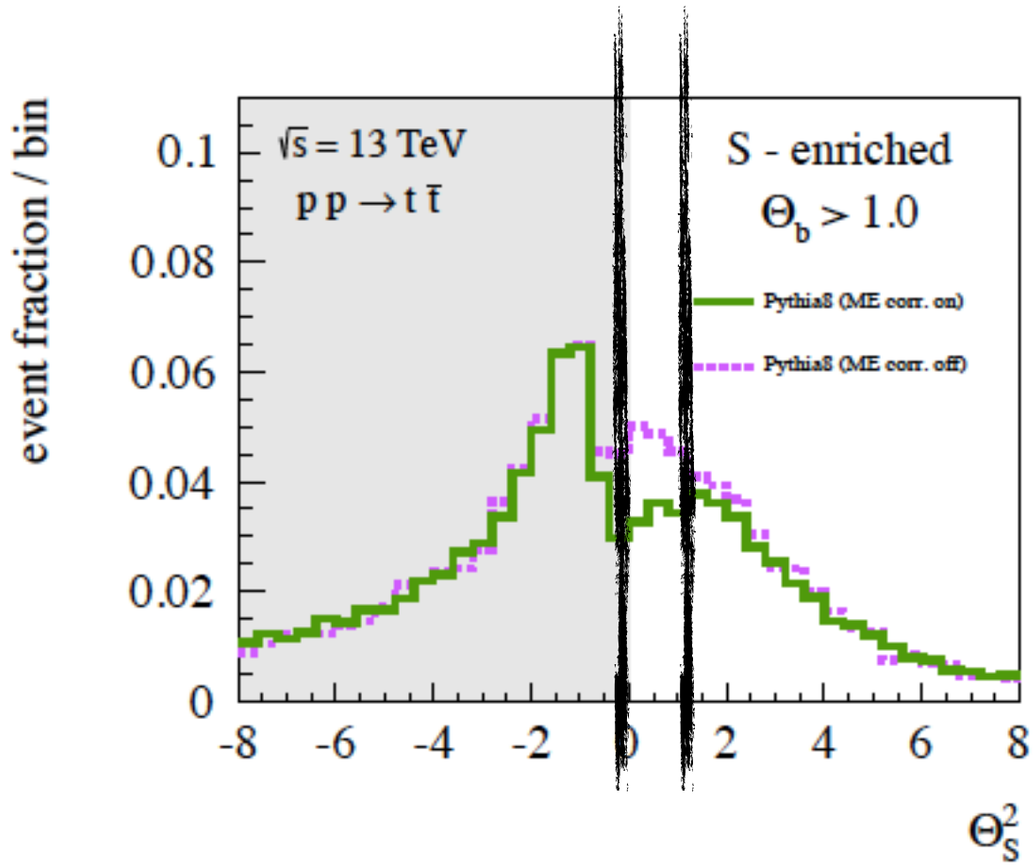
fiducial cuts: $\epsilon_{\text{fid}} = 45\%$

b/ top tagging : $\epsilon_{\text{top}} = \epsilon_b = 50\%$

soft drop (two prong) : $\epsilon_{\text{SD}} = 55\%$

signal region: $\epsilon_S = 30\%$.

angle top - b: $\epsilon_{\Theta_b} = 30\%$.



total efficiency: $\epsilon_{\text{total}} \simeq 0.55\%$

$\mathcal{L} = 300\,\text{fb}^{-1}$ $\quad \mathcal{N}_{\text{on}}^{[0.0,1.0]} = 85,$ $\quad \mathcal{N}_{\text{off}}^{[0.0,1.0]} = 125$

difference is statistically significant at 4 σ level after Run II

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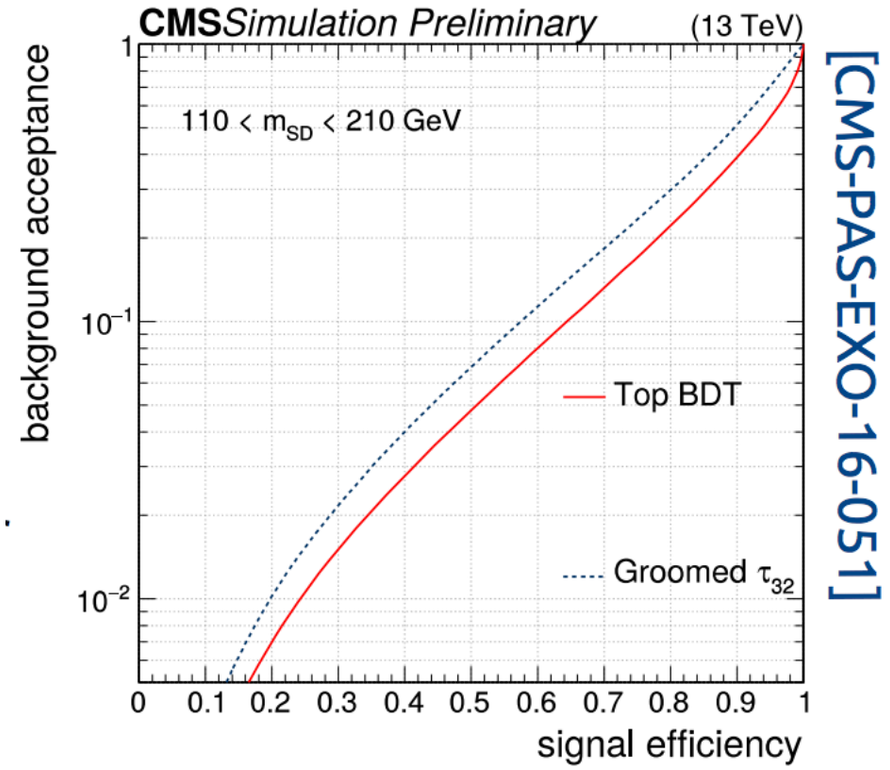
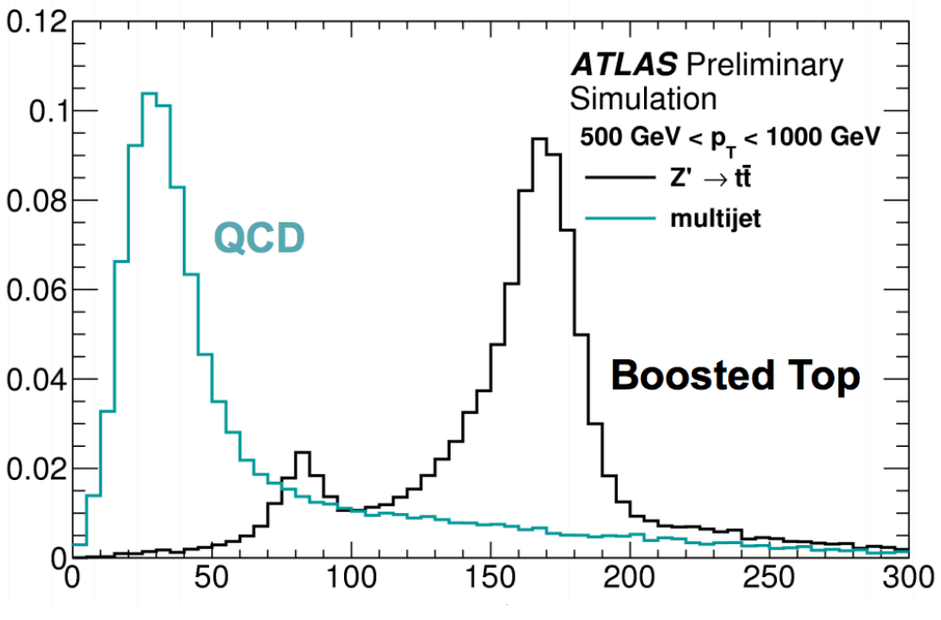
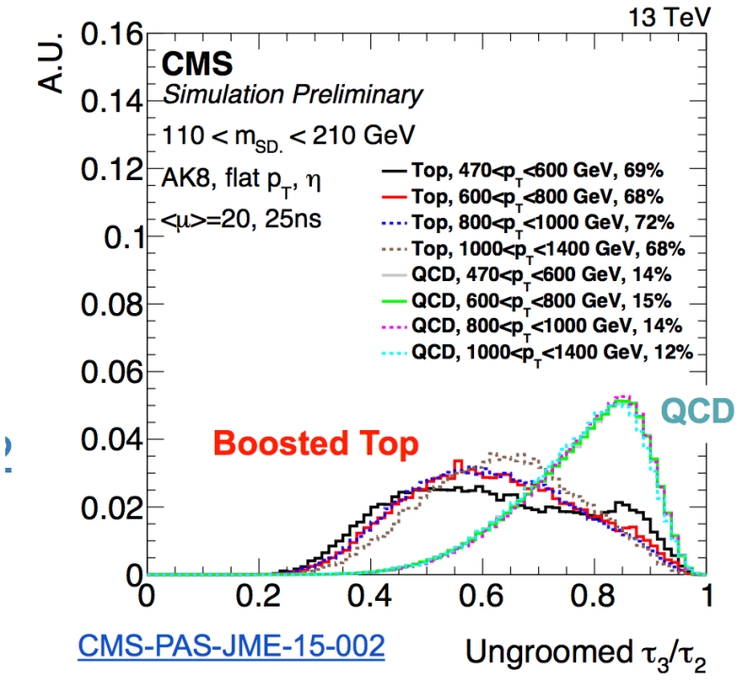
Top tagging

Recap

- Top Tagger:
  - some observable (or MVA) that provides separation between QCD and Top jet.
- Traditional taggers:
  - jet mass, usually groomed, (e.g "soft-dtop" m_{SD})
  - Jet shapes (N-subjettiness, energy correlation functions, D_3 …) (see: [1108.2701], [1402.2657], [1411.0665])







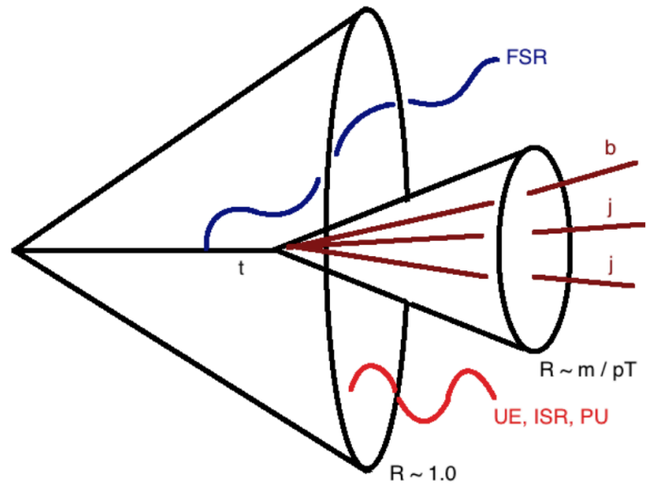
Top tagging

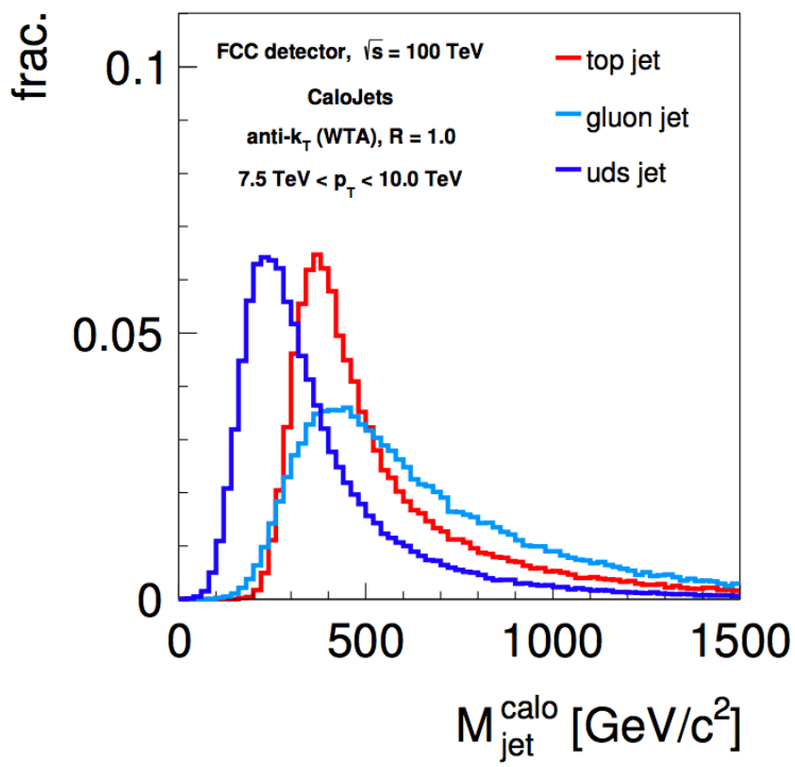
Recap

- Problem with traditional taggers:
  - First removing soft radiation (ISR, Pile-Up, **FSR**) by grooming techniques

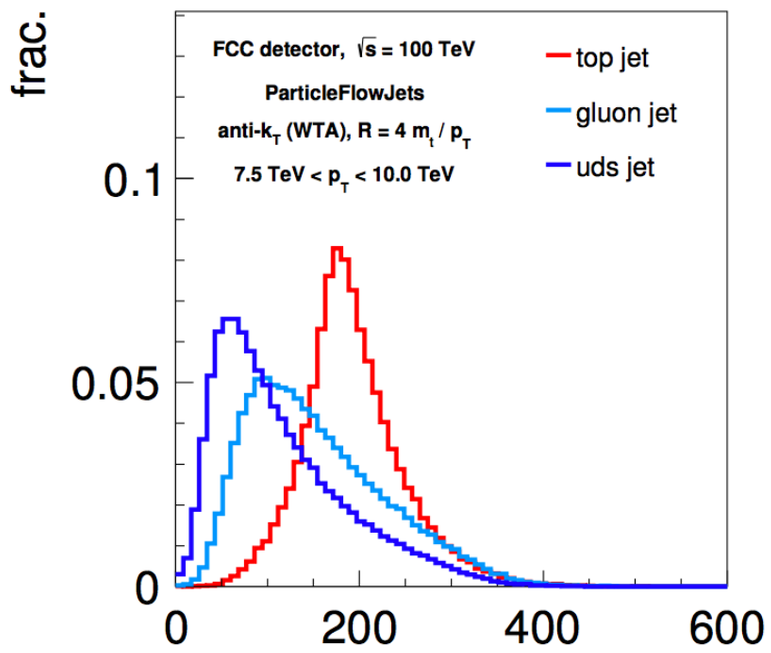
    ⇒ spoils potential discrimination in FSR patterns (dead-cone)
  - attempt to reconstruct top kinematics (mass, shapes)

⇒ typically do not address FSR pattern



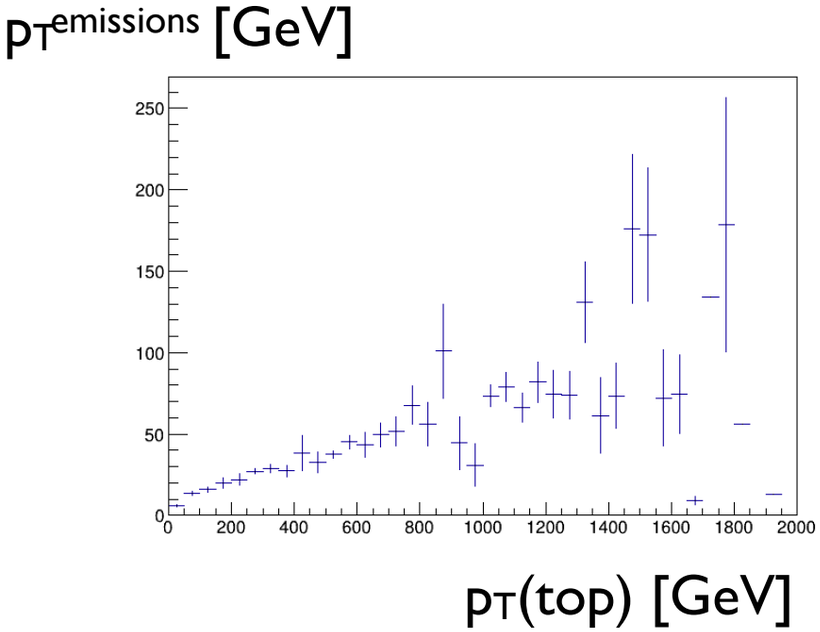


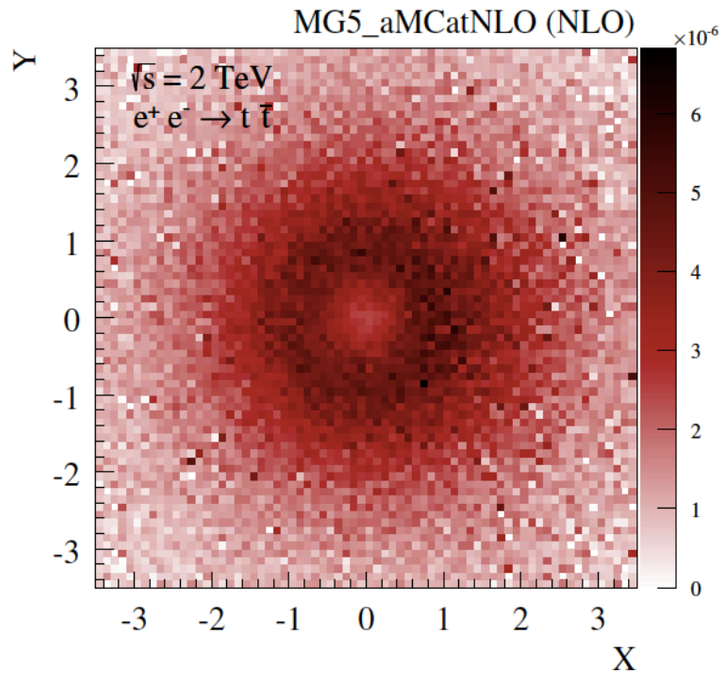
groom



Dead Cone in top tagging?

- Can the FS radiation pattern be exploited for QCD discrimination?
  - the effect is **small** (although log-enhanced at high energies)
  - operates at similar angular scales **R ~ m/p_T** as top decay products
- **top decay products** produce their own FSR (much larger than top, because **m_q ~ 0** !!)
- Even assuming top decay contribution can be subtracted (and we know already from semi-lep it is hard), still have to **deal with diffuse background ISR and PU**
- Looks very challenging!

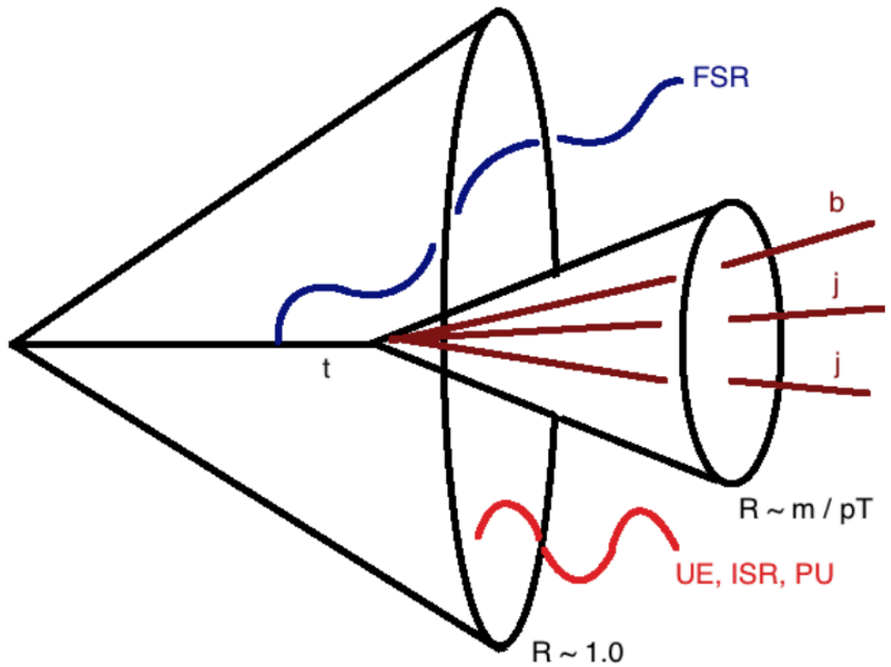




Possible ways out

Recap

- Find **optimal jet radius** (possibly dynamical):
  - large enough to **catch all decay products** and D.C. eff
  - small enough to **reduce impact of uniform soft radiat** (scales like area ~ R^2)
  - Proposal is **R = 2-4 m/p_T** (e.g. see [1503.03347])



- Most naive jet **observable** (although dominated by decay):

$$X_{DC} = p_T\,(R<R_{DC}) \,/\, p_T^{JET}$$

- CNN (**jet images**) can learn difference in FSR patterns but one has to be careful of:
  - not applying grooming pre-processing (that will kill FSR)
  - subtracting top decay from jet image
  - apply filters to look for DC structure

- DNN using full PF candidate information (e.g. **DeepAK8** in [CMS-DP-2017-049]) should learn out-of-the box

Summary
for the LHC

- Dead Cone is a **fundamental prediction** of **QCD/QED** that has been known for long time, but never conclusively measured

- **Measuring** it precisely can help in **constraining** various Monte Carlo/**Parton Shower** models

- May have direct applications to jet substructure and **Top tagging**

- Effect is expected to be **small at the LHC** (need large boost to enhance)

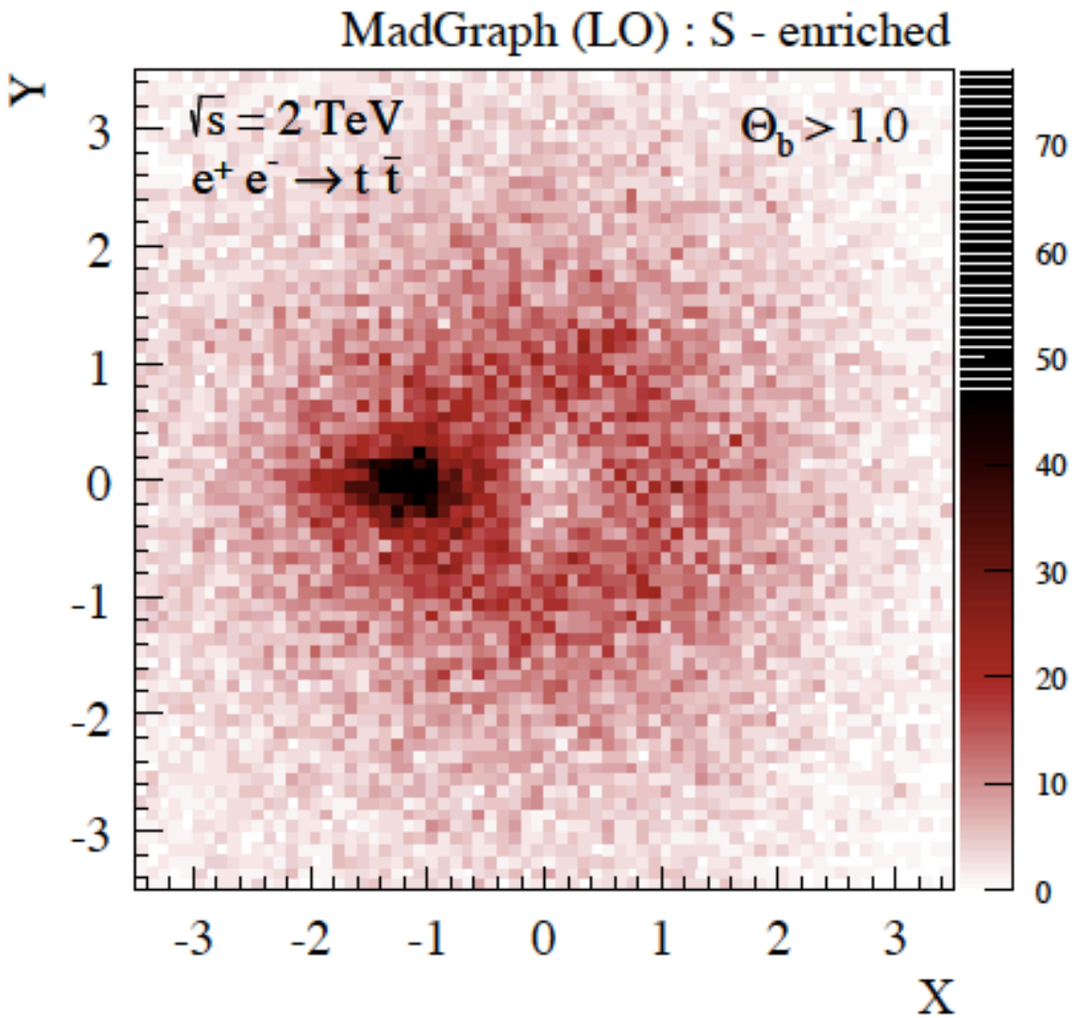
- Traditional taggers do not exploit it (actually kill it) because FSR is pruned away

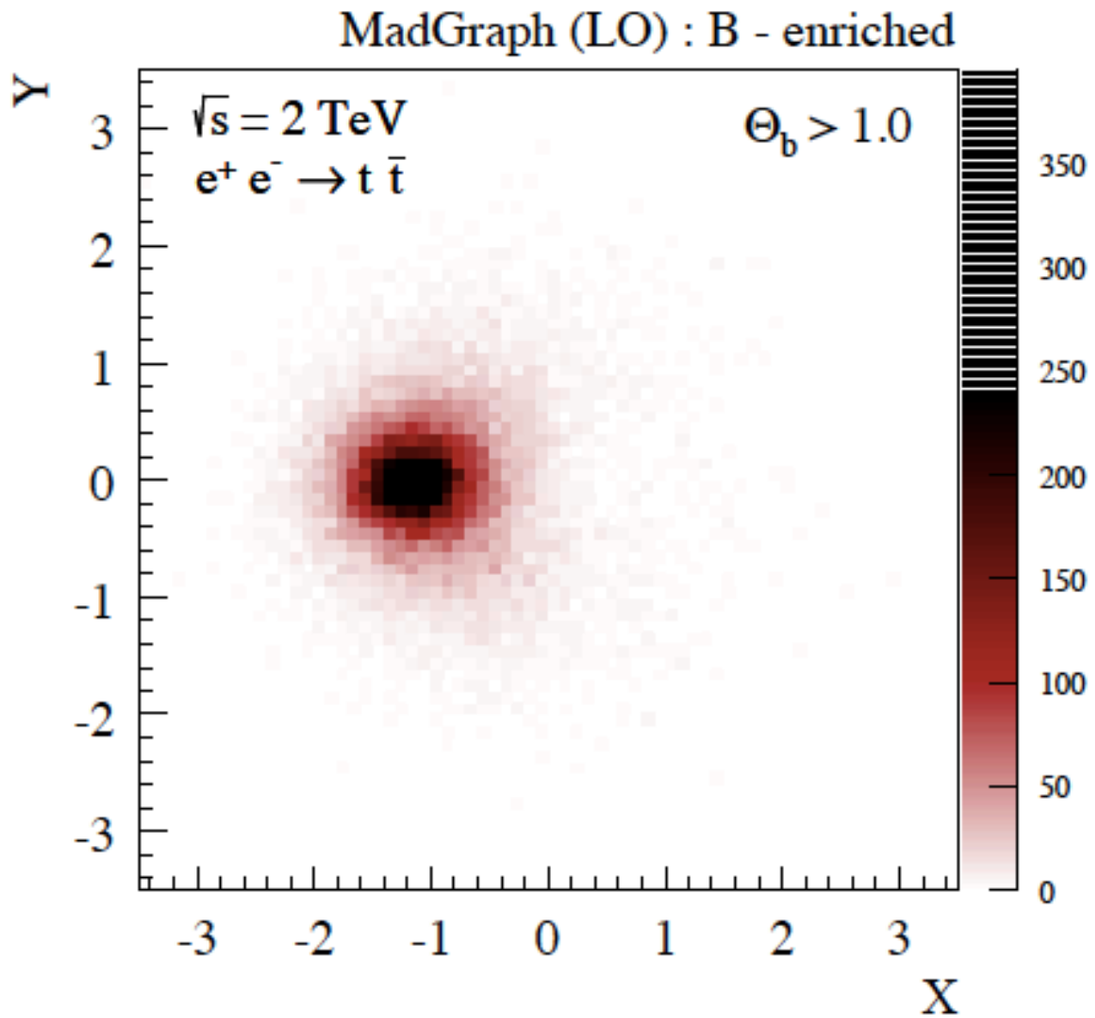
- More advanced taggers based on **Deep Learning** and **jet constituents lists** might already be taking advantage of it.

- To be Checked!

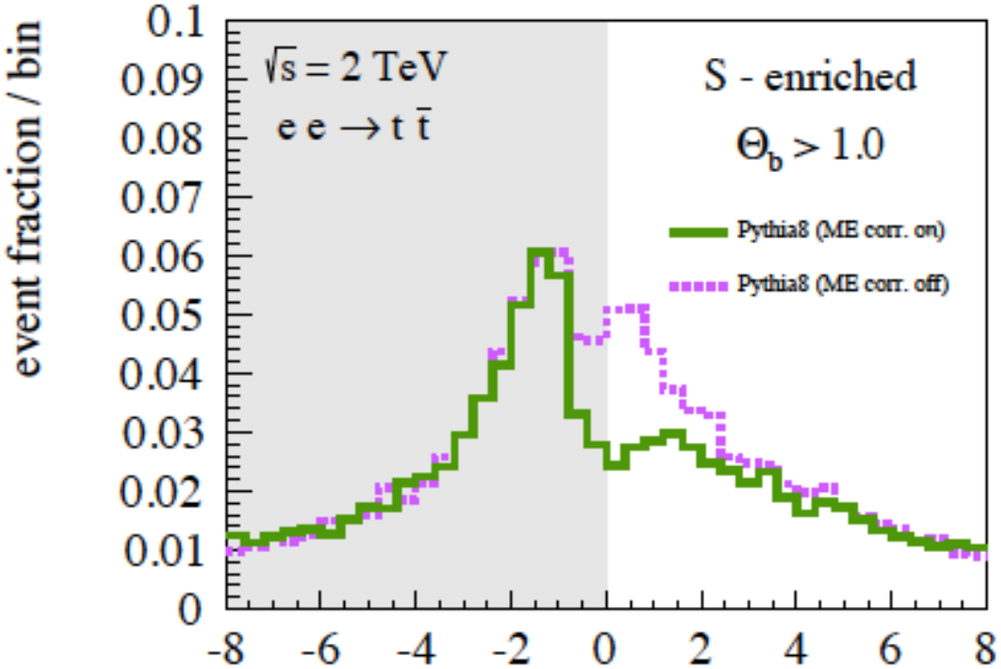
Backup

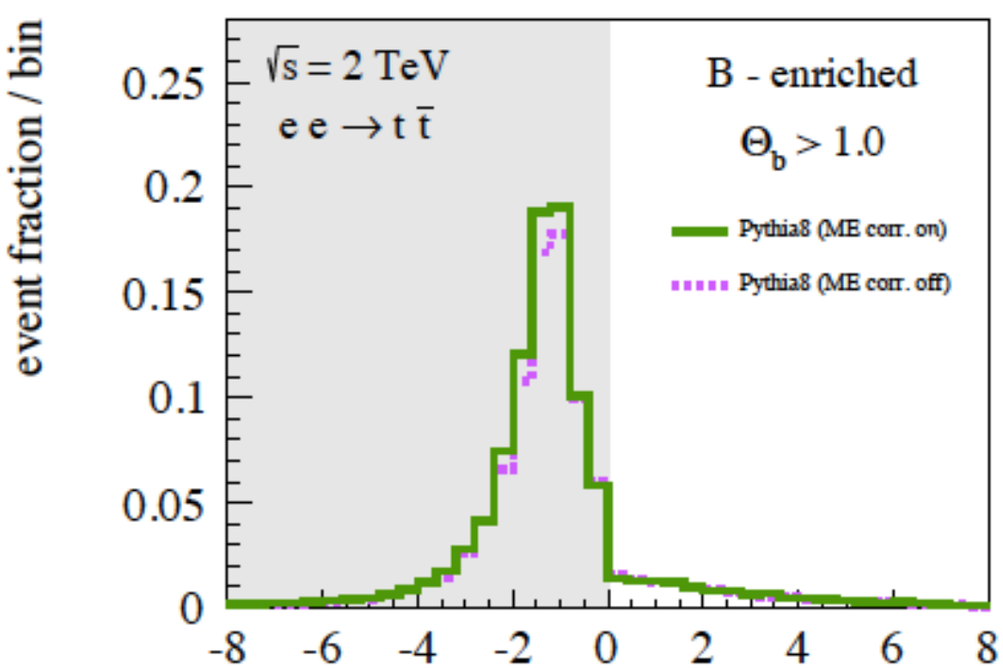
Full analysis with e^+e^- events

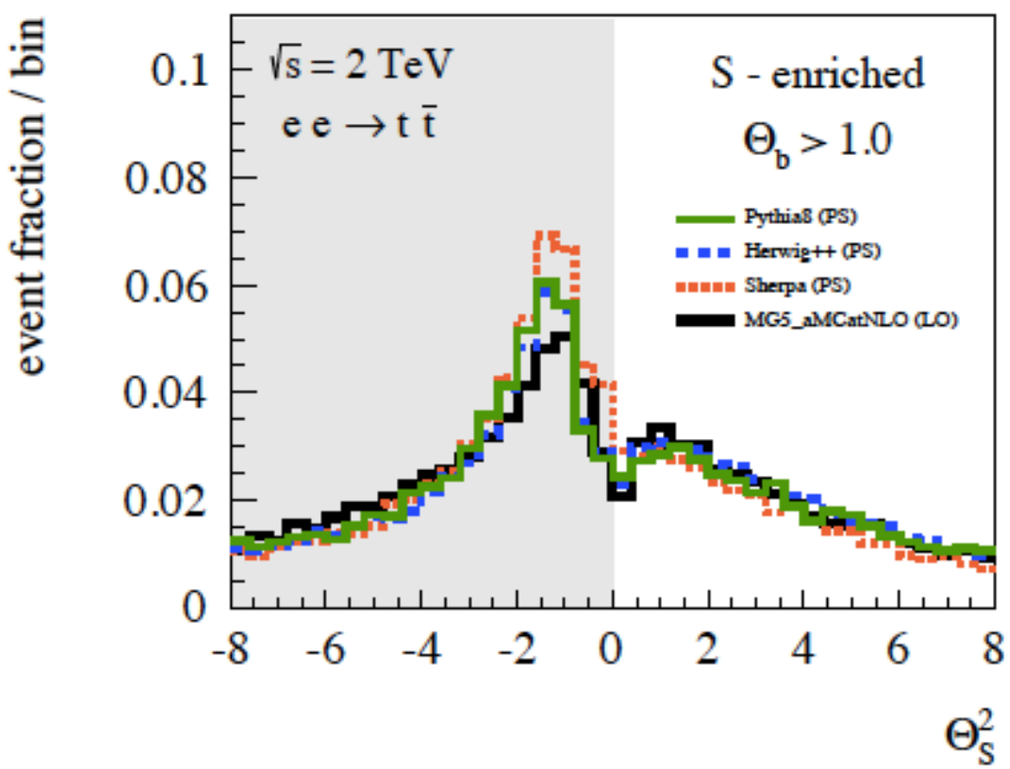


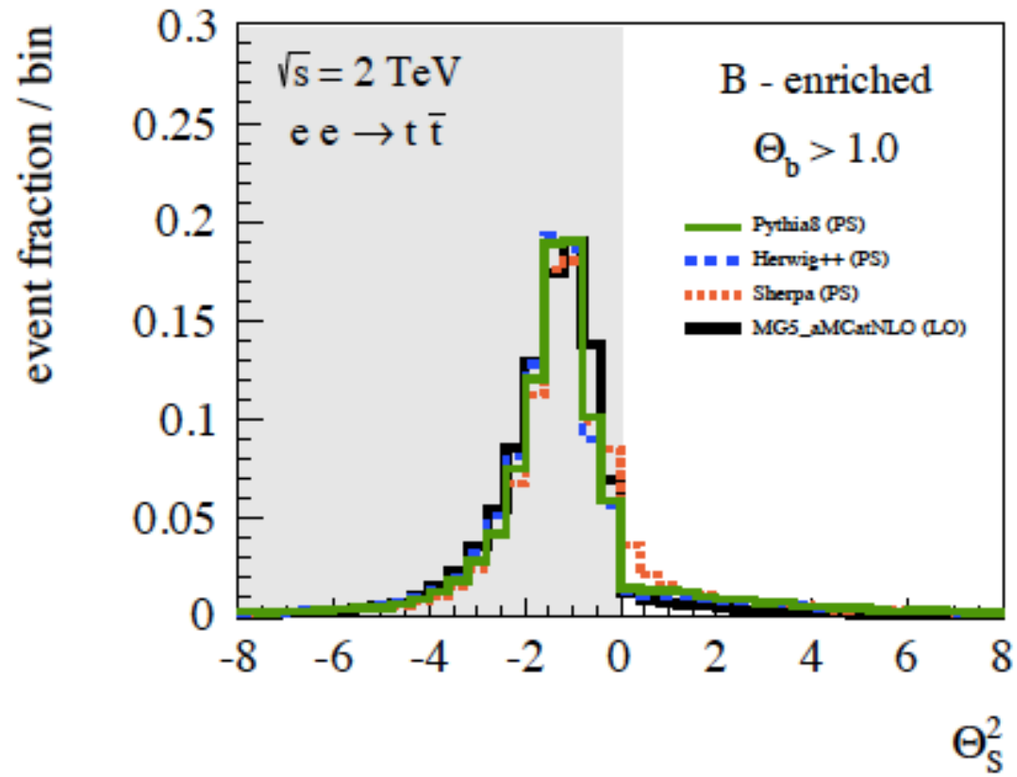


Full analysis with e^+e^- events

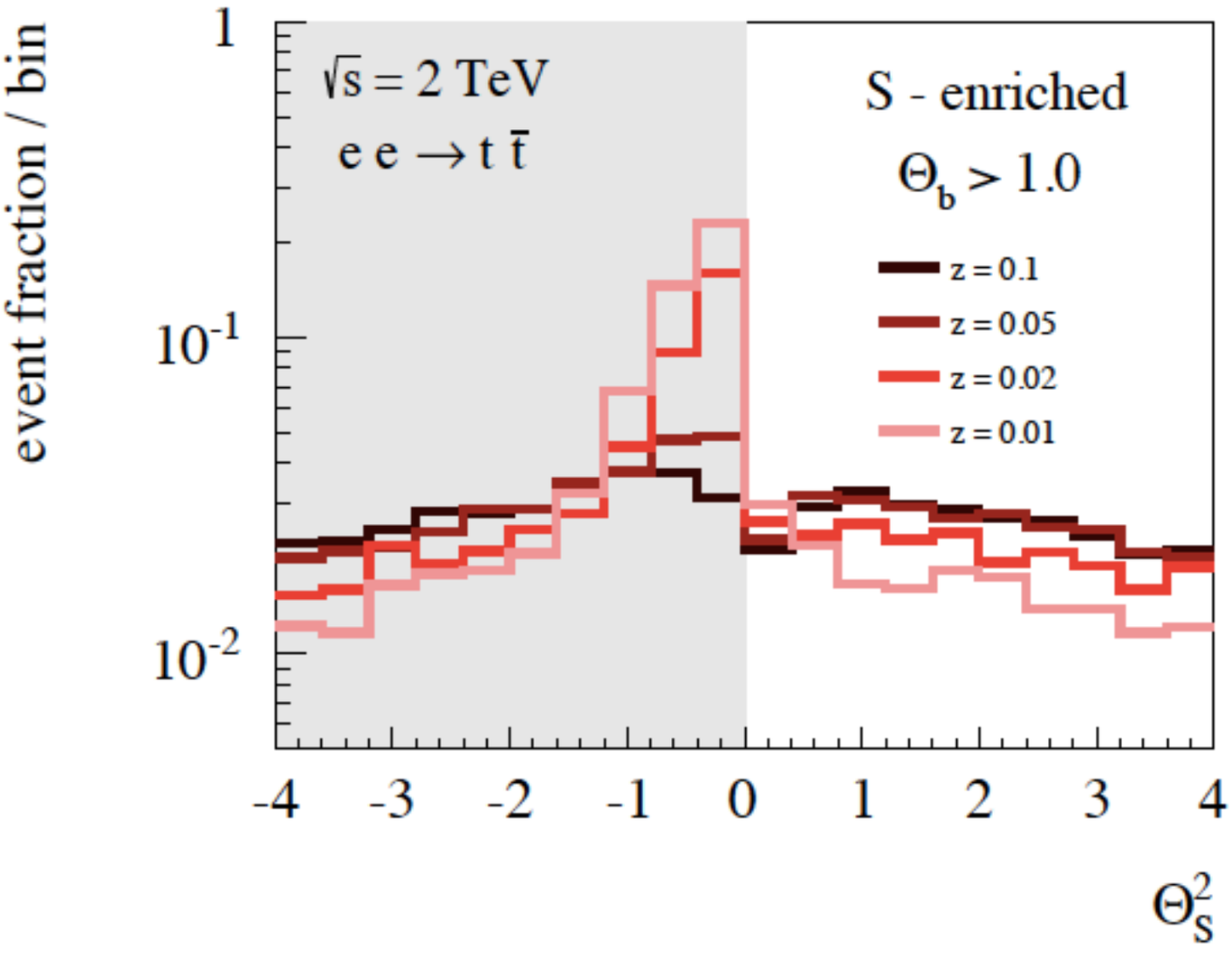








Interference with rad. in decay



Analysis Strategy

find the FSR gluon

- find the **top direction** by solving for E_z^{miss} :

  - **do not make use of m_{top} constraint** otherwise **bias** our background to look like our signal

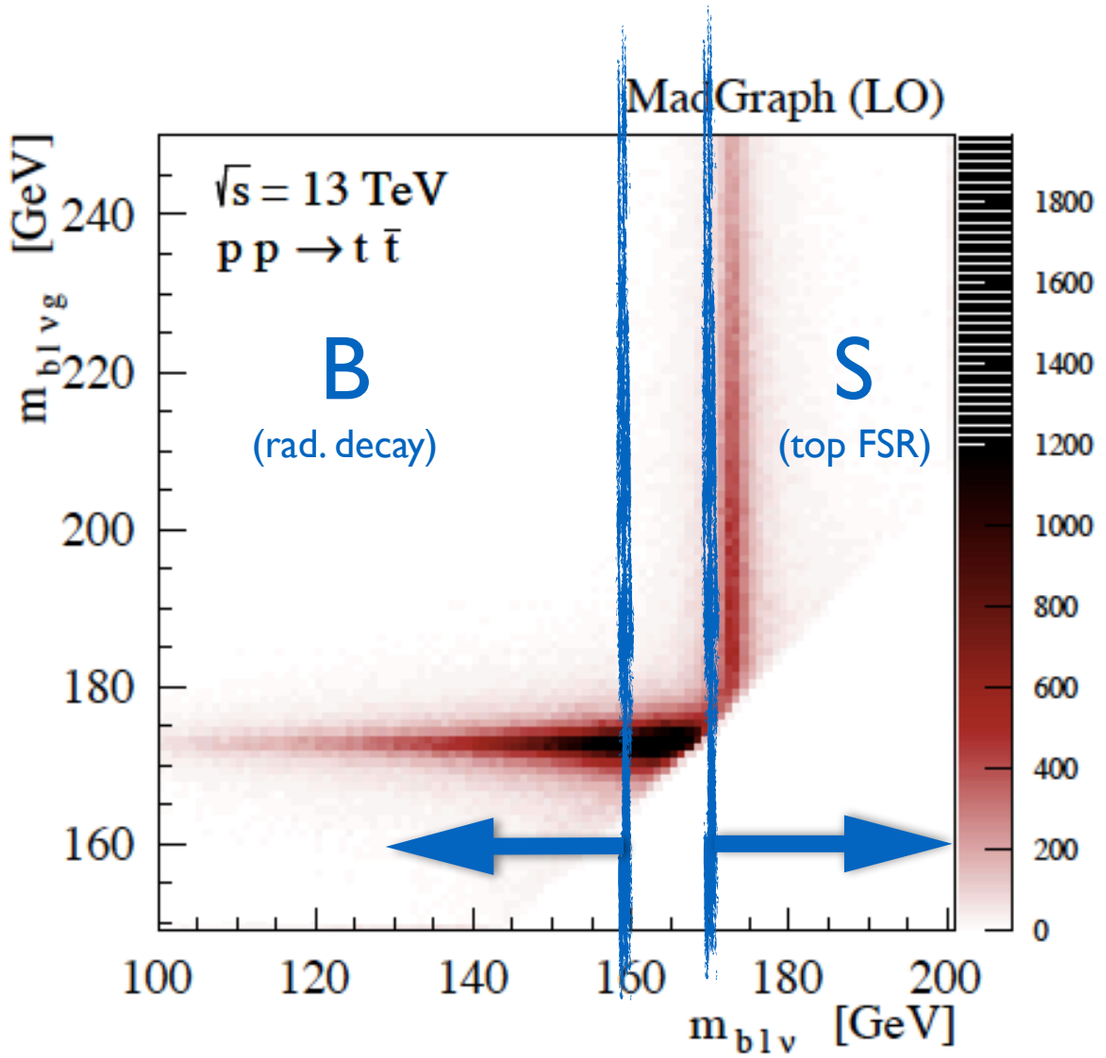
  - make use of **W mass constraint** (2 solutions)

  - solve **degeneracy** by checking consistency with hypothesis:

    - radiation in production (**S**)
    - radiation in decay radiation (**B**)

- Having all components at hand (b, l vu, g) define **S** and **B** enriched regions:

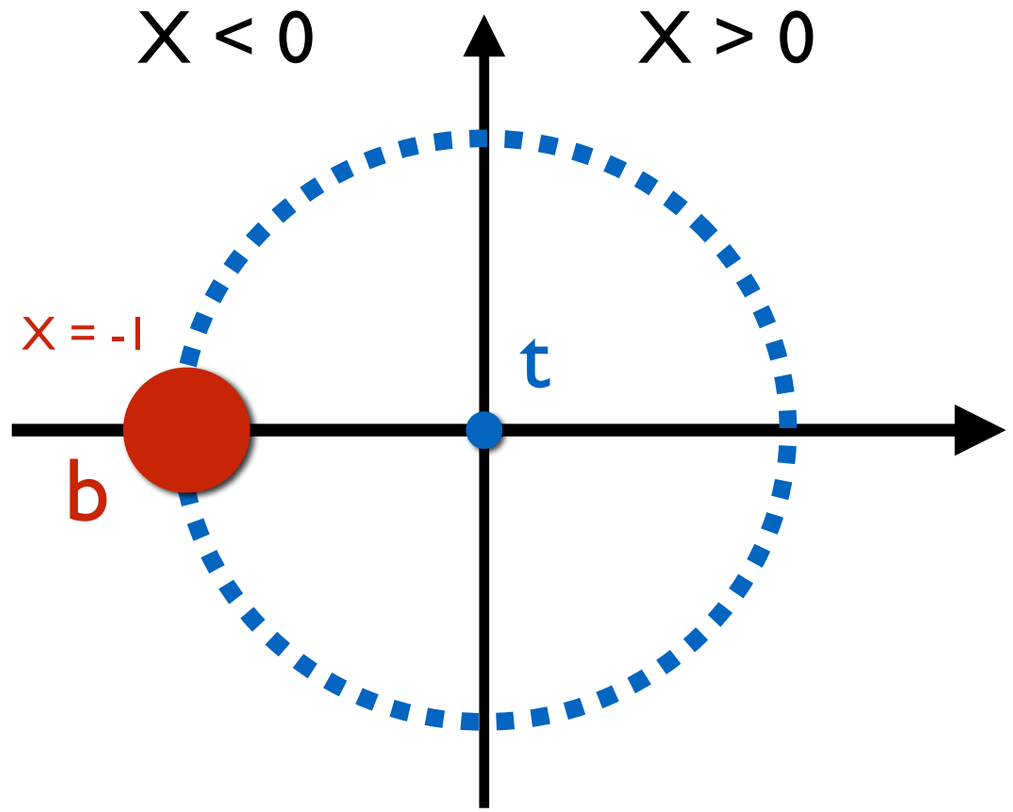
$$S\text{-enriched:} \quad m_{b\ell\nu} \in [170, 200]\ \text{GeV},$$
$$B\text{-enriched:} \quad m_{b\ell\nu} < 160\ \text{GeV}.$$

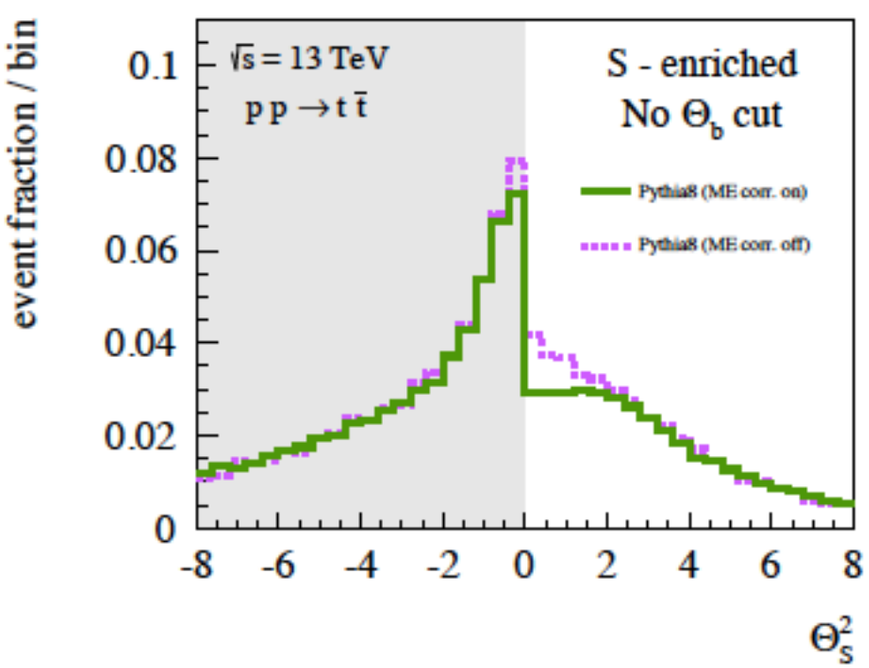


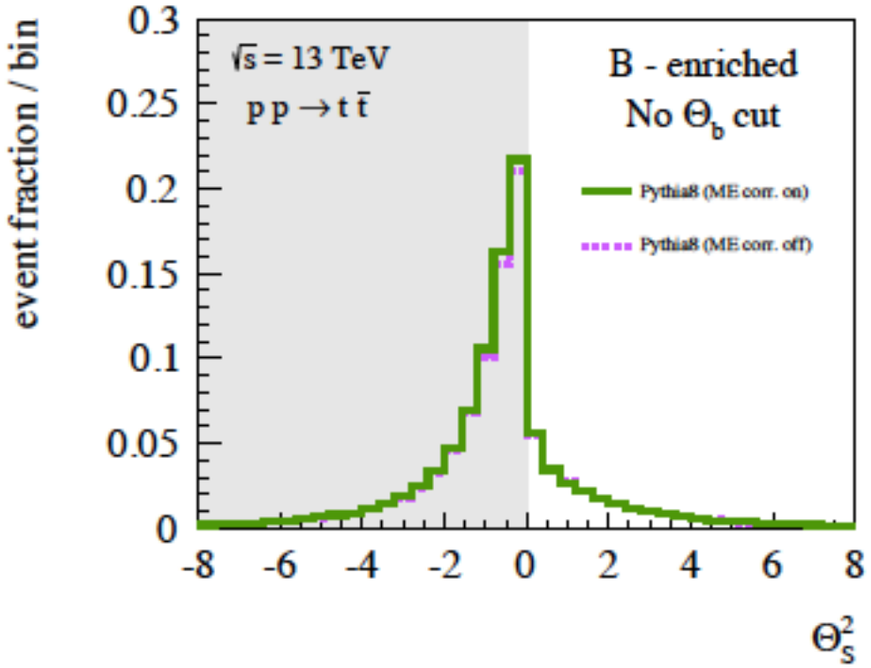
Observing the Dead Cone

- **b-jet** sits exactly where top **FSR is max**
- rotate the event such that **b-jet lies on the X axis**
  → look the "**other way**"
- in one dim. , define:

$$\Theta_S^2 \equiv \mathrm{sign}(X)\,\Theta^2$$







Observing the Dead Cone

- Due to kinematics, **b-jet** sits exactly where **top FSR is max**

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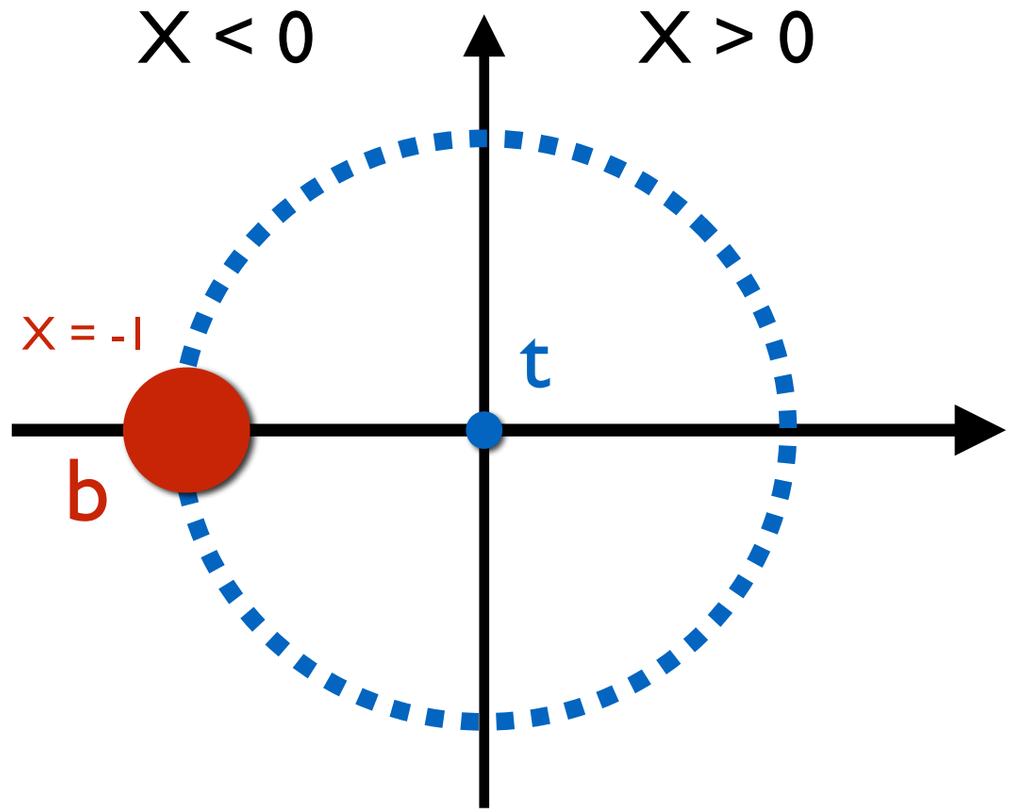
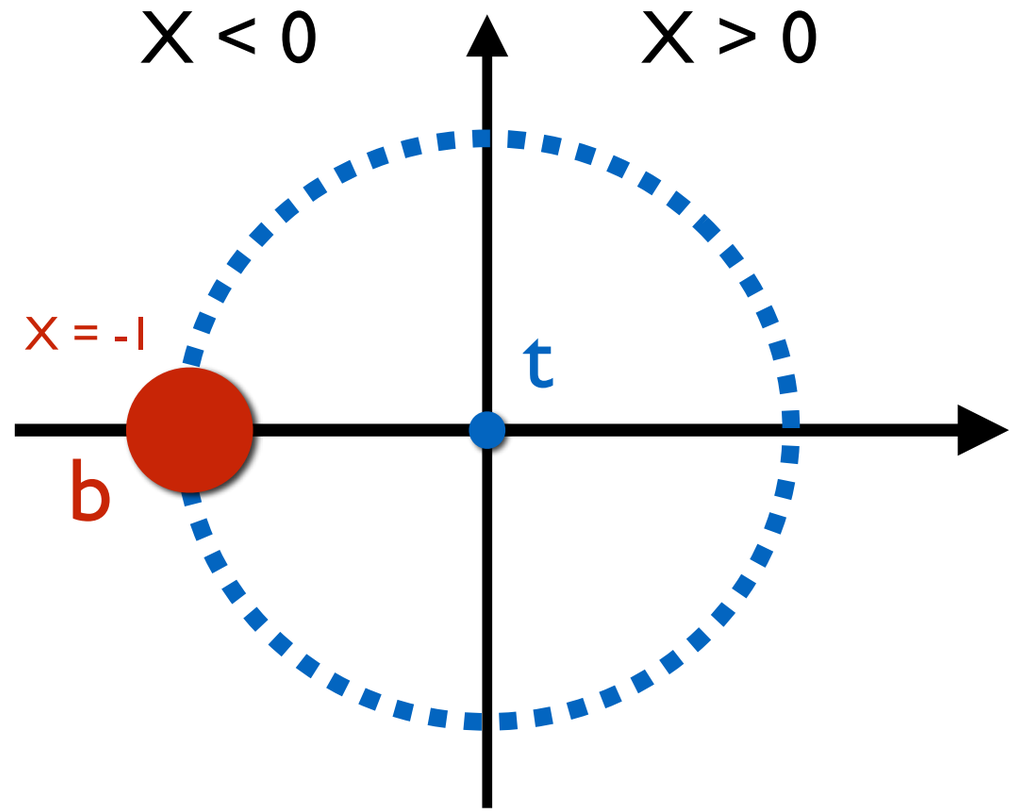


Observing the Dead Cone

- purity can be increased by "pushing the b-quark away"

  → require **larger angle** between t and b:

$$\Theta_b > 1.0$$



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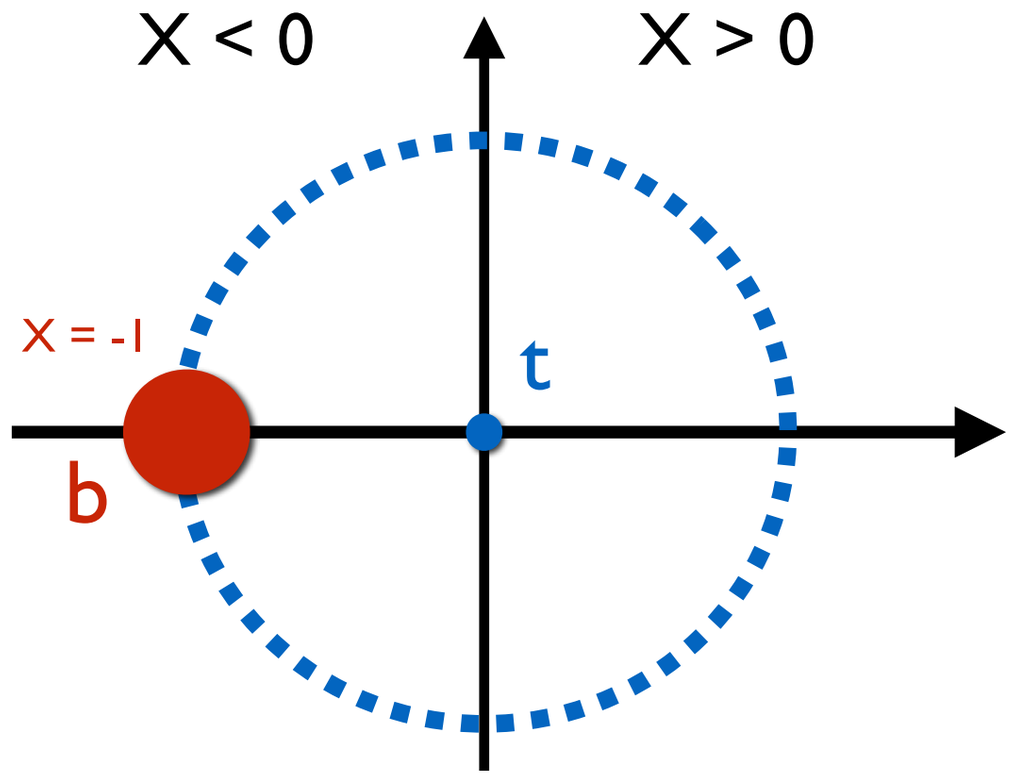

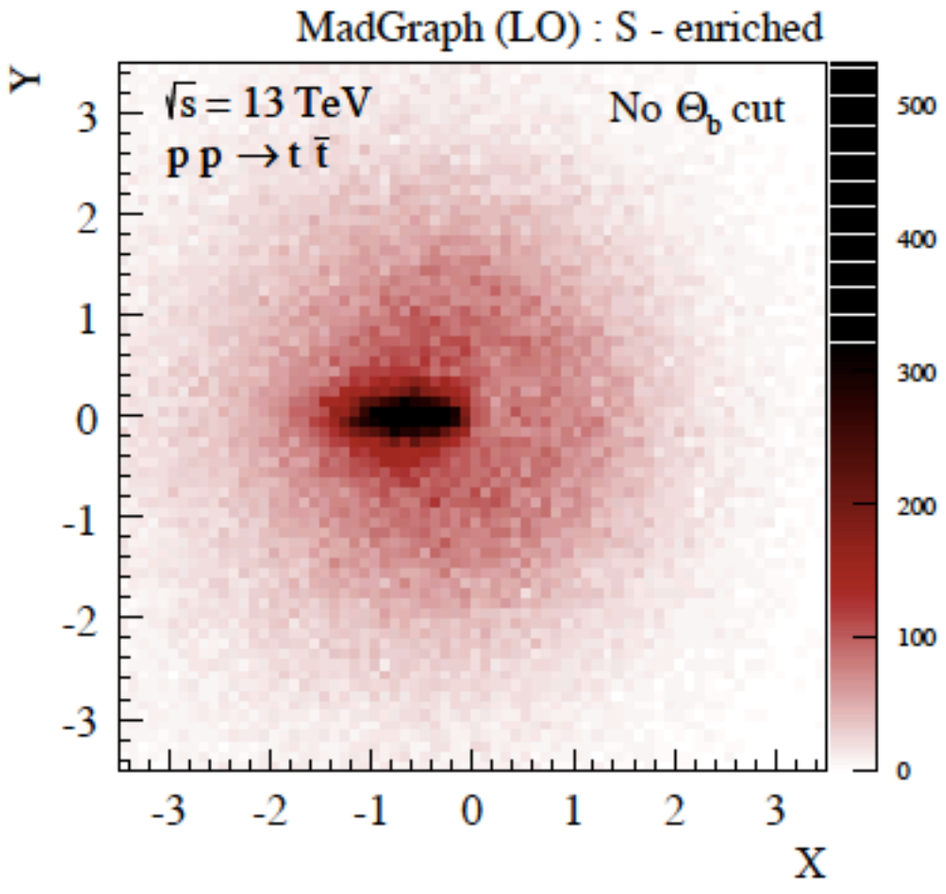

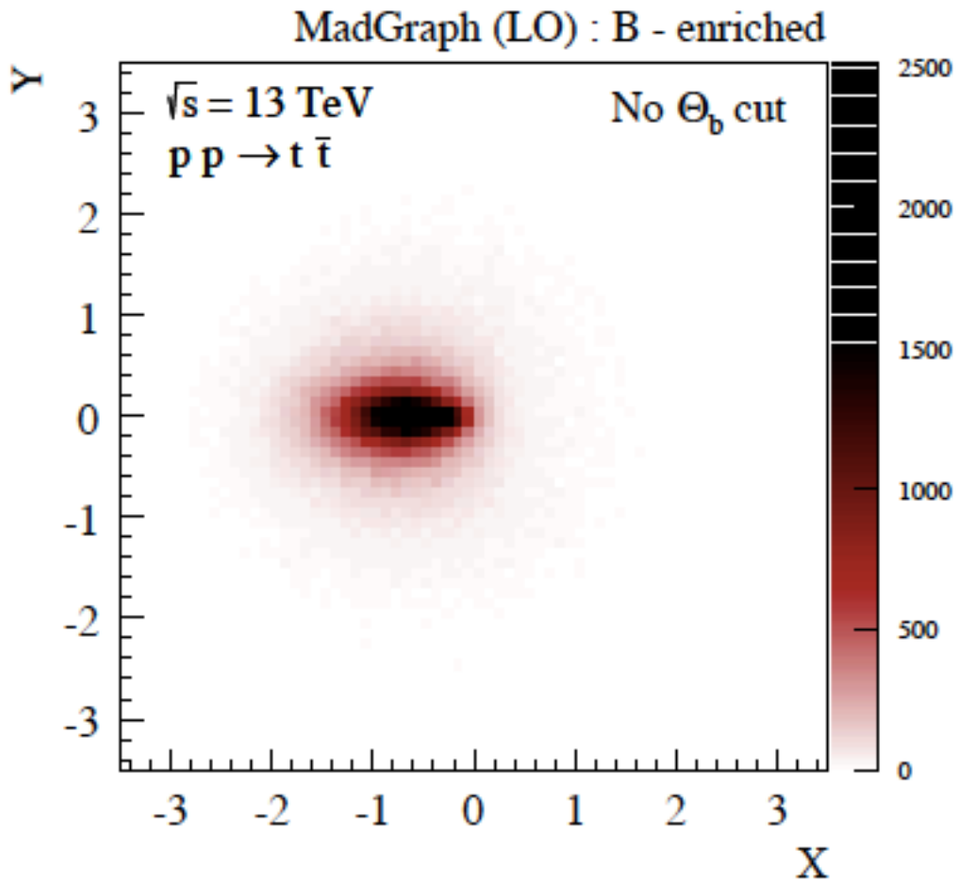

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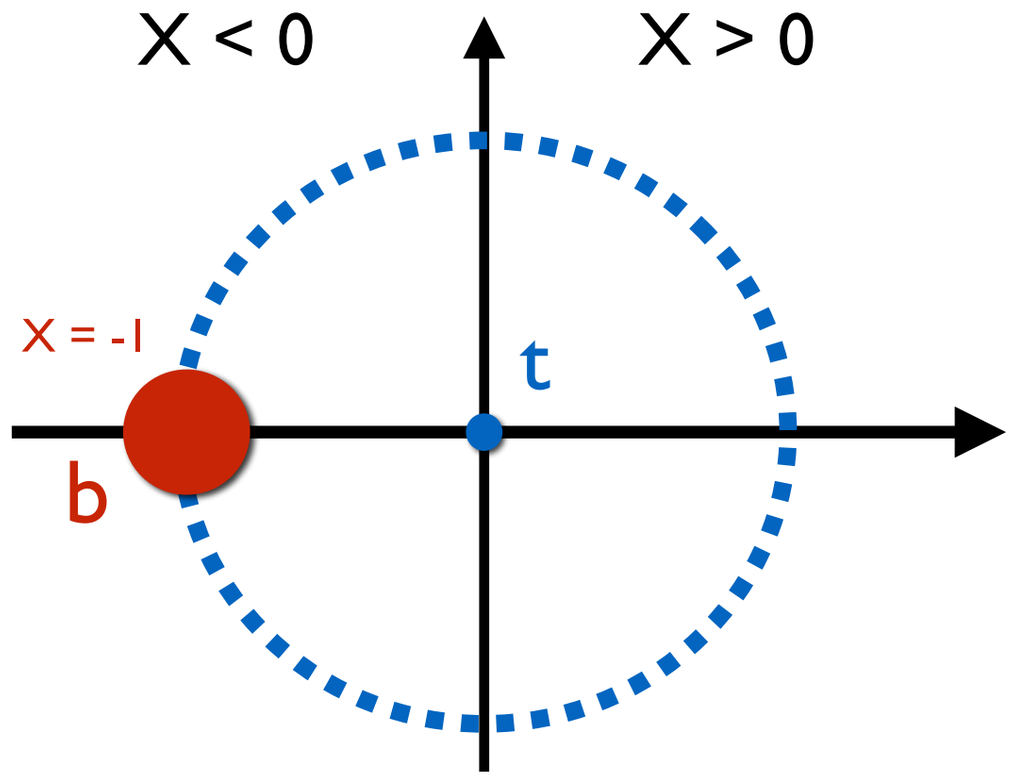

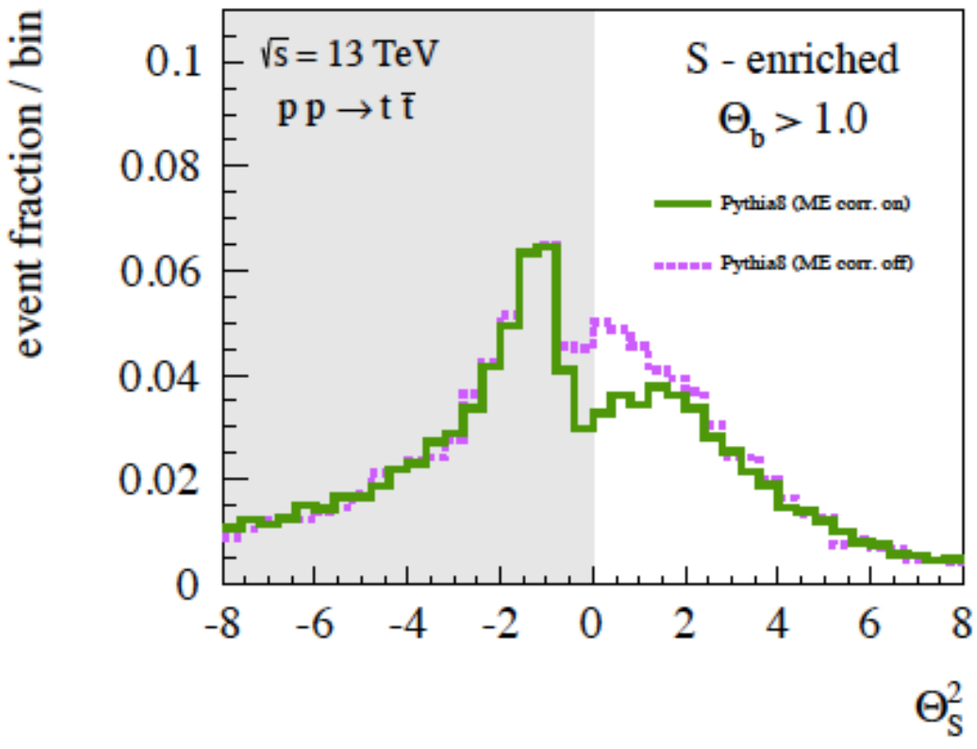

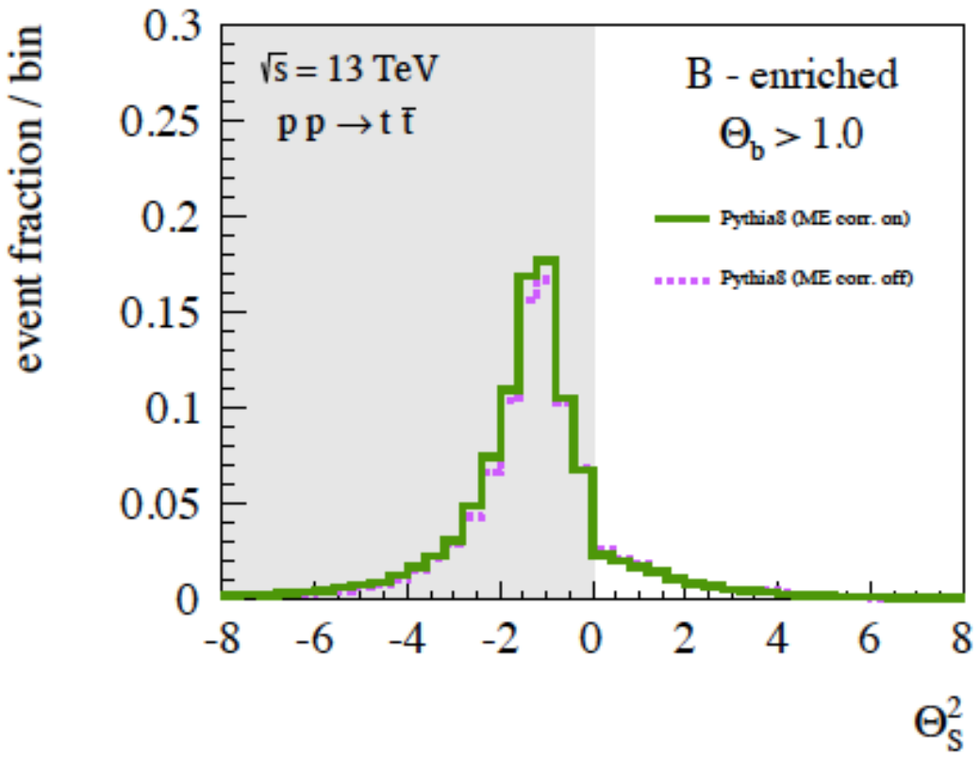

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