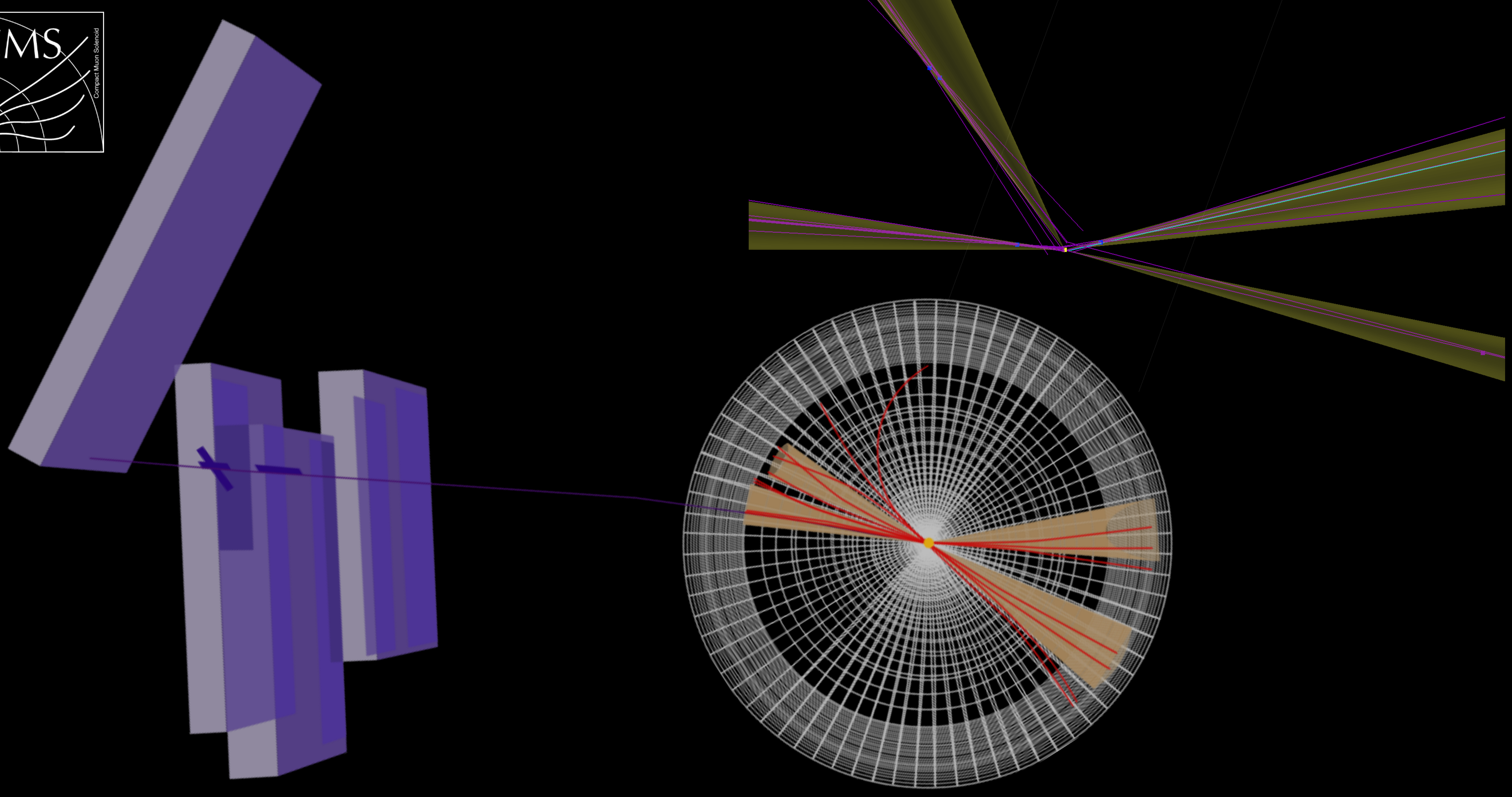


Higgs to bb and Pixel-Phase-II R&D

Caterina Vernieri, FNAL and LPC Distinguished Researcher

7.27.2017

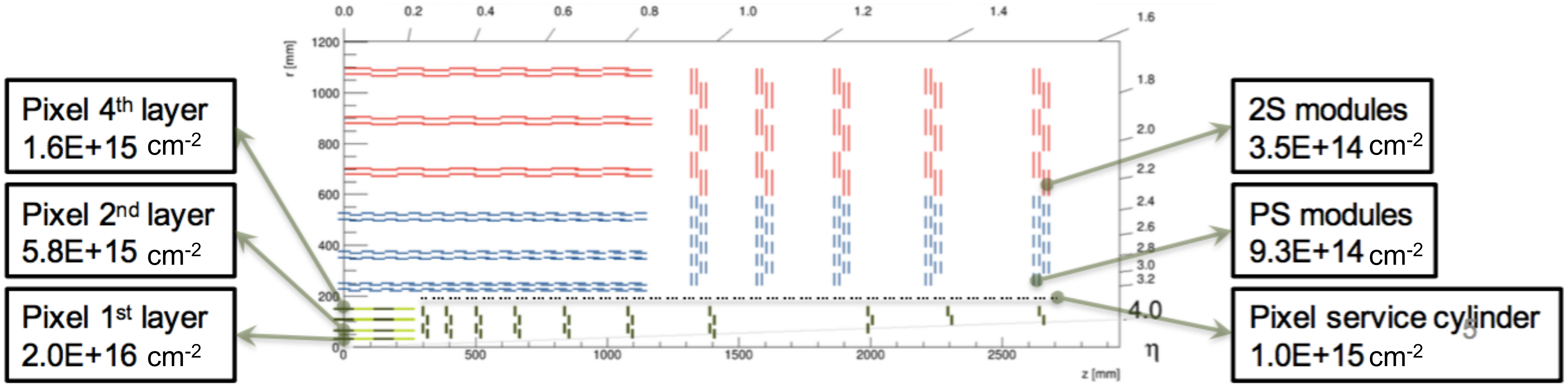
Lorenzo Uplegger, Ryan Rivera, C.V. (FNAL)
Irene Zoi (Hamburg U) Julia Thom, Nereida Ramirez (Cornell U.)

Phase–II Pixel upgrade

Ongoing R&D plan to develop a new pixel tracking system to operate at HL-LHC

- To maintain a high tracking and b-jet identification efficiency at luminosities up to $7 \cdot 10^{34}$ $cm^{-2}s^{-1}$ and operate up to 200 <PU>
- It will extend the η coverage from the present η =2.5 to η =4
- Radiation tolerance up to 3000 fb^{-1}

- Different lines of investigation for Phase-II:
  - **Better acceptance per module**/hermeticity ⇛ **slim edge sensors**
  - Higher instantaneous luminosity ⇛ **high granularity** ⇛ **small pitch sensor**
  - Higher integrated luminosity ⇛ **high radiation tolerance** ⇛ **thinner sensors**

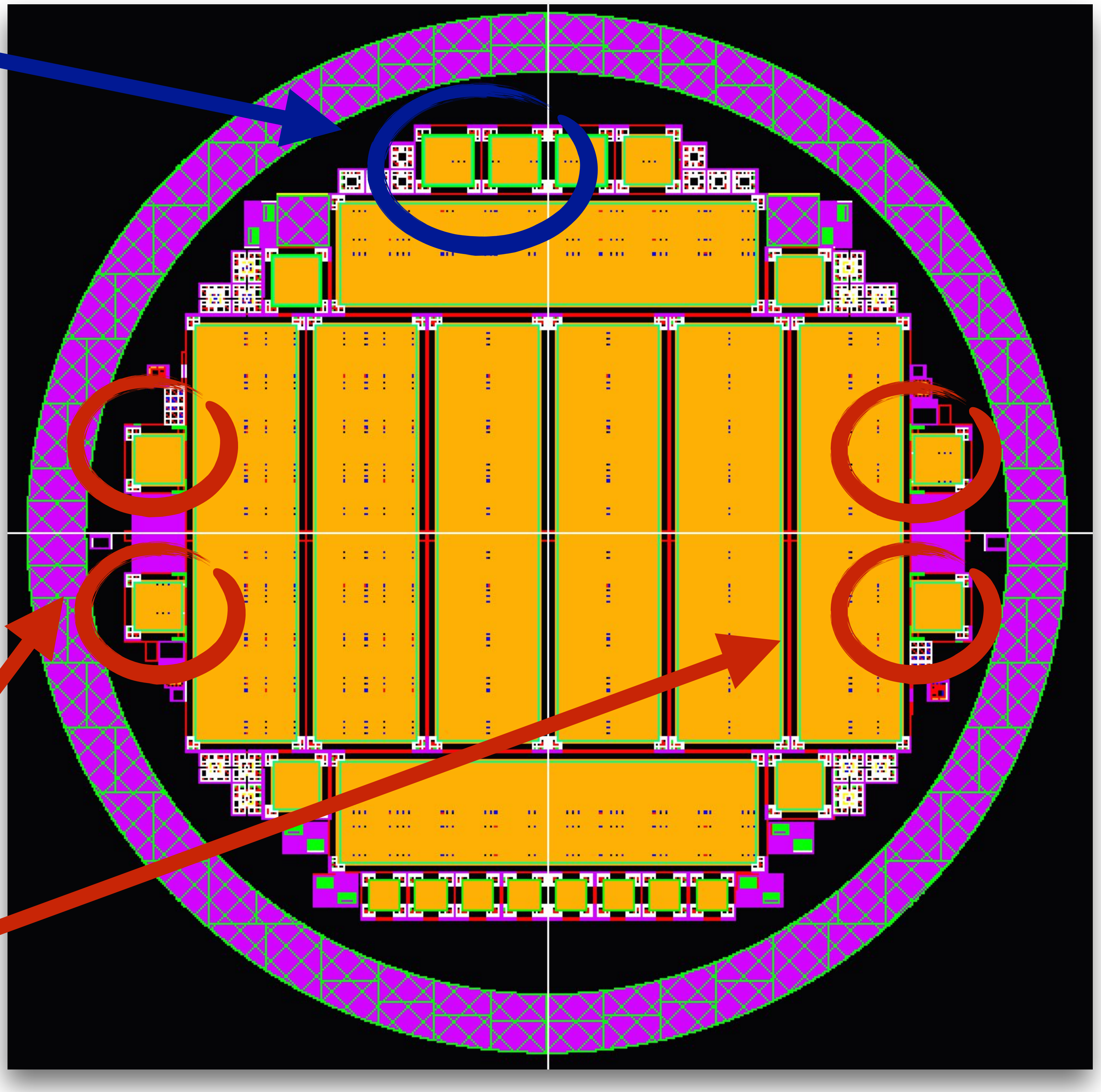


n-in-n

Prototypes were produced along with the pixel sensors of the CMS Forward Pixel detector and tested at Fermilab at the Test Beam Facility

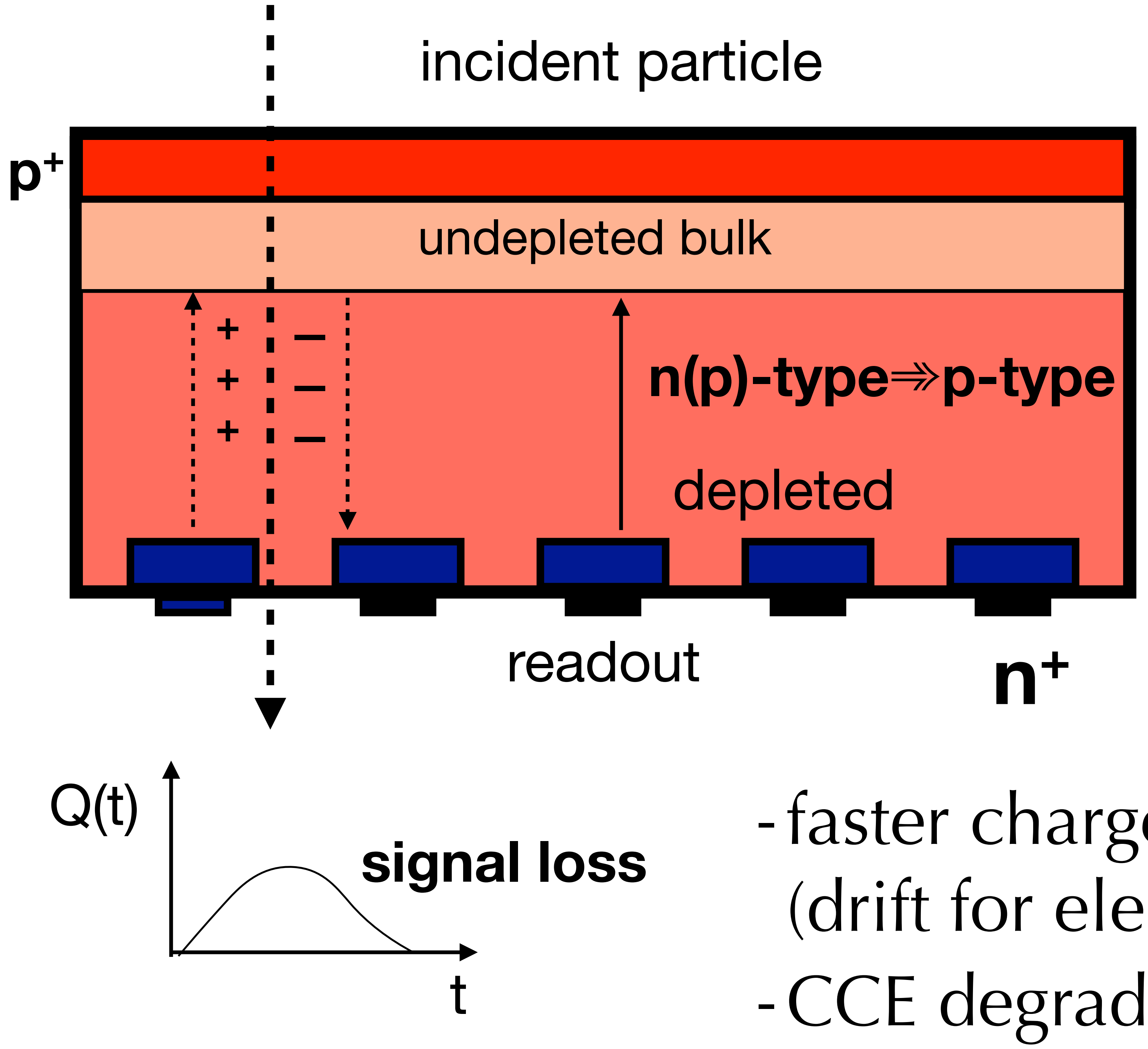
Small pitches

- n-in-n (double sided)
- 300μm thick
- FZ, 3-5 kΩcm



Slim edge

n-in-p *or* n-in-n



- faster charge collection (drift for electron is larger)
- CCE degradation

The approach saves money and relies on a established process

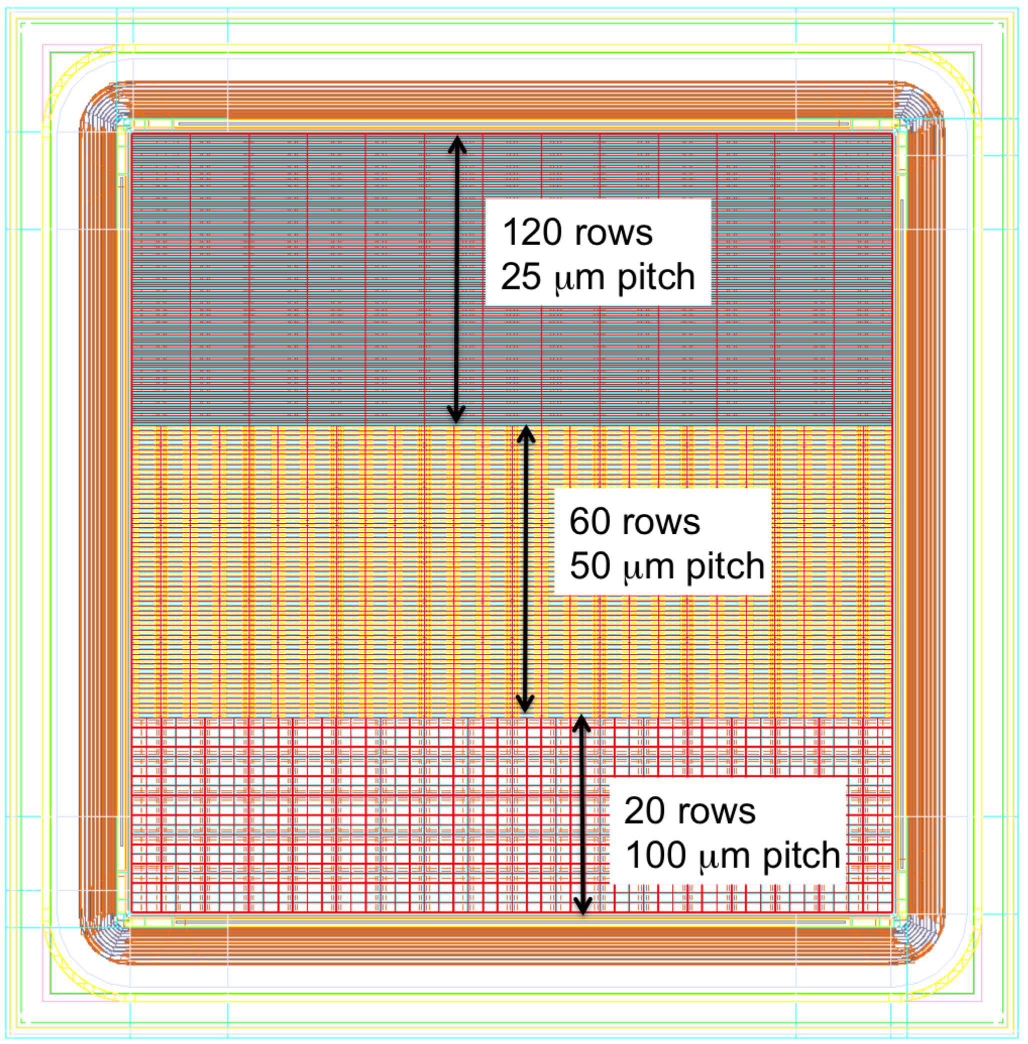
Small pitch sensors

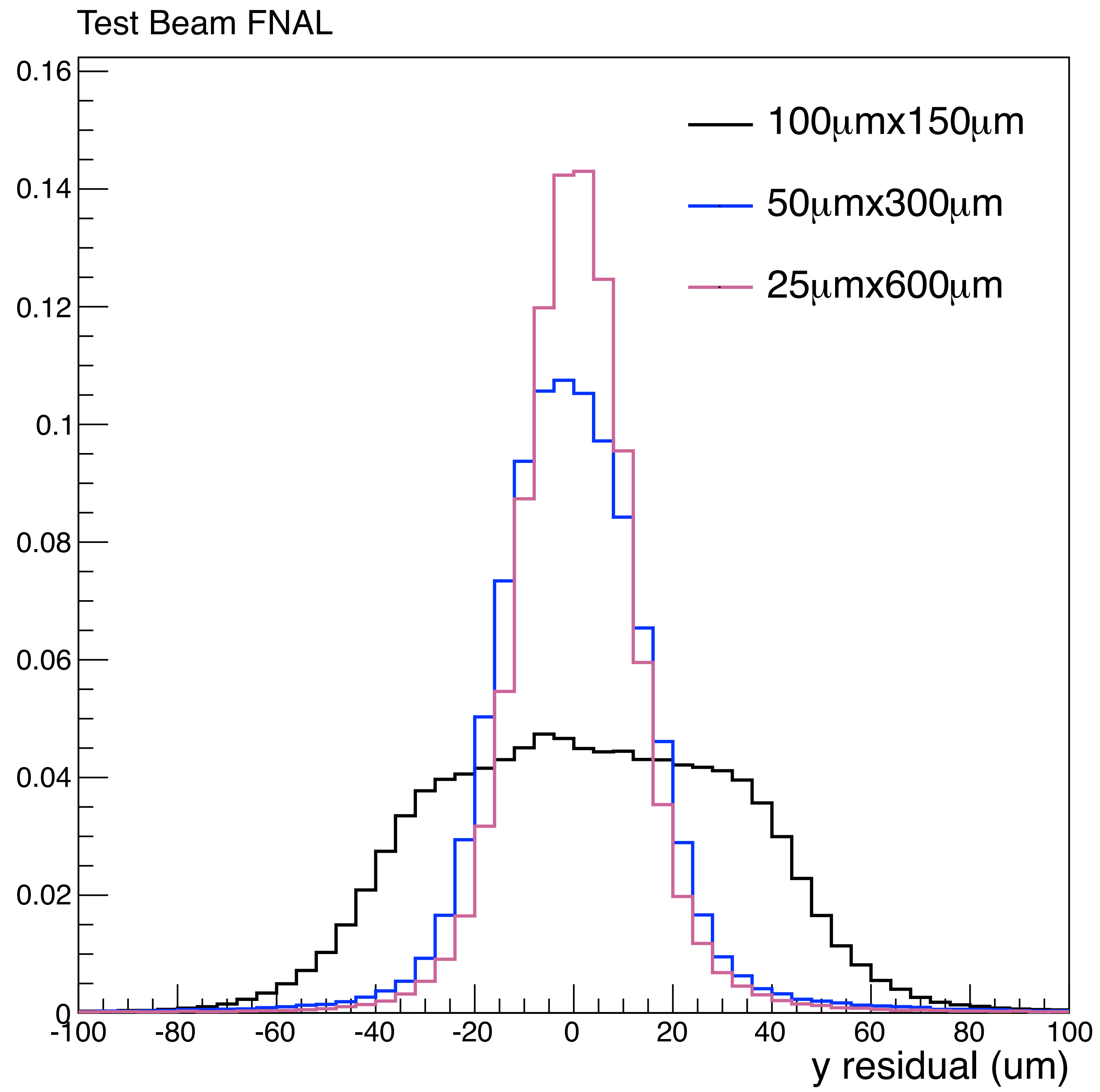
Require bump-bonding patterns compatible to PSI46 ReadOutChip (Phase-I)

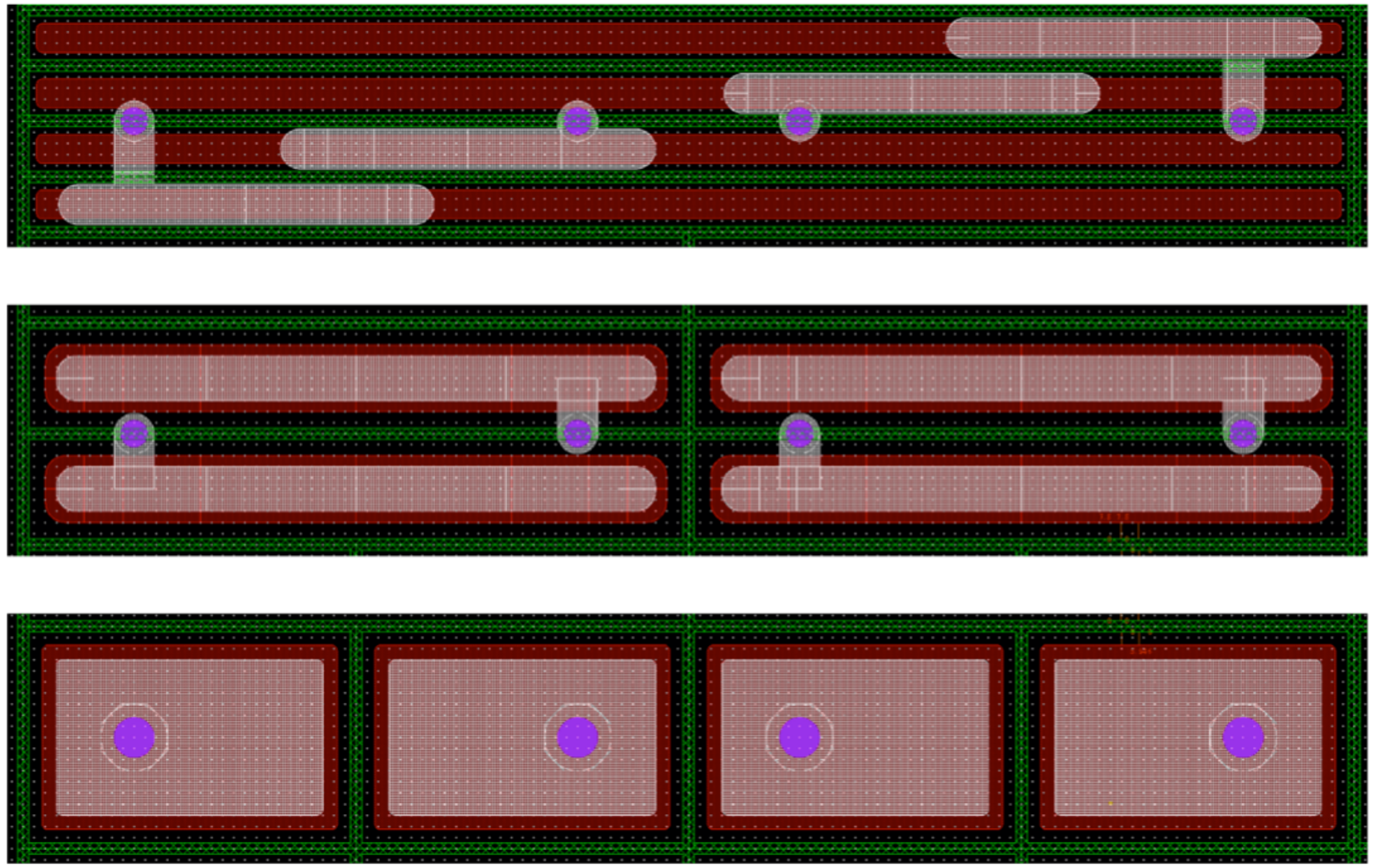
Maintained the same pixel area $100 \times 150 \mu m^2$ that is implemented in the Phase-I design

Single ROC sensors split in 3 regions with 3 different pitches

* The hit **resolution is 5.8µm** for **25µmx600µm pixels**







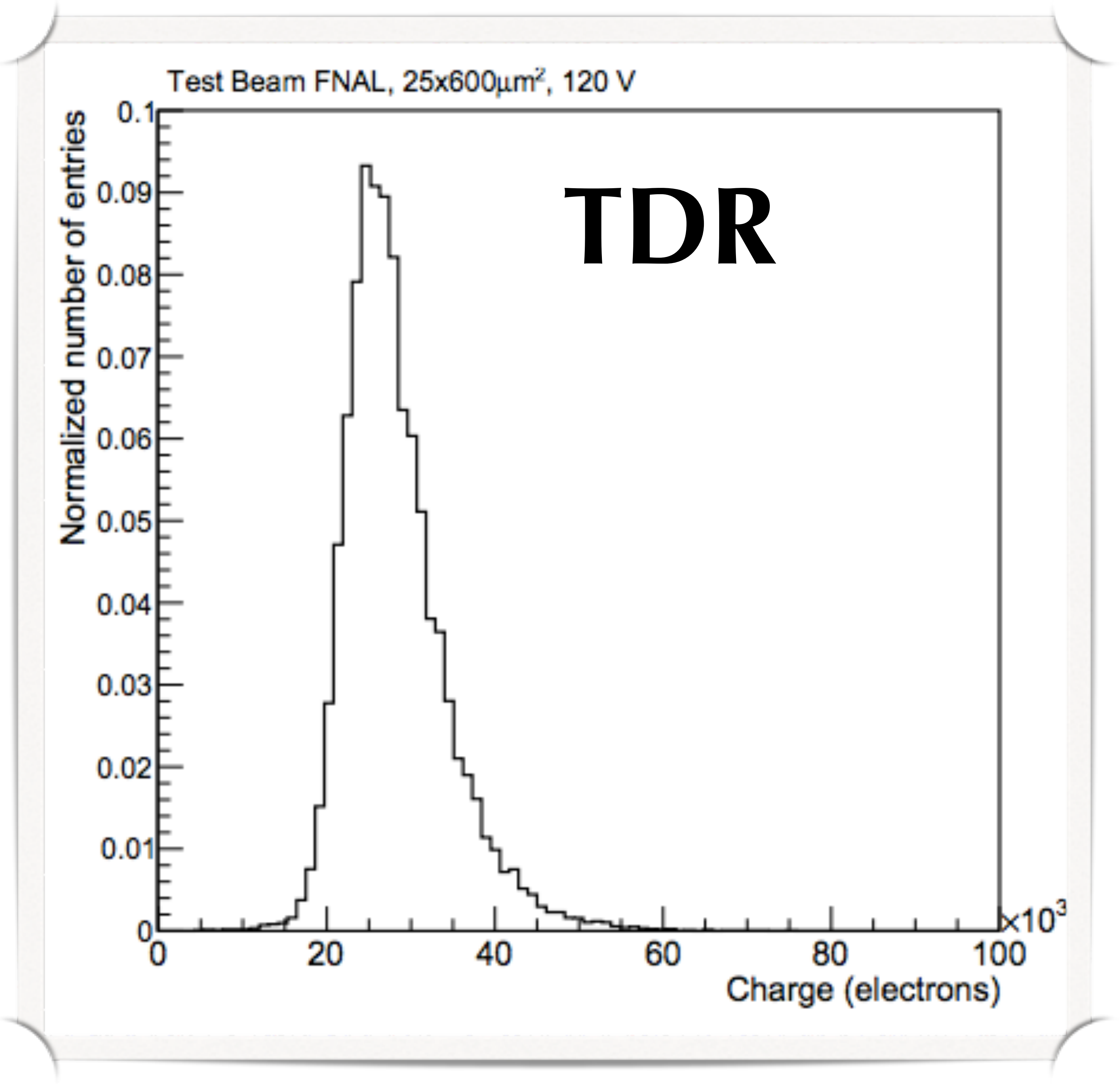
n+	→ 13 µm
gap	→ 3.5 µm
p+	→ 5 µm
gap	→ 3.5 µm
Pitch	→ 25 µm

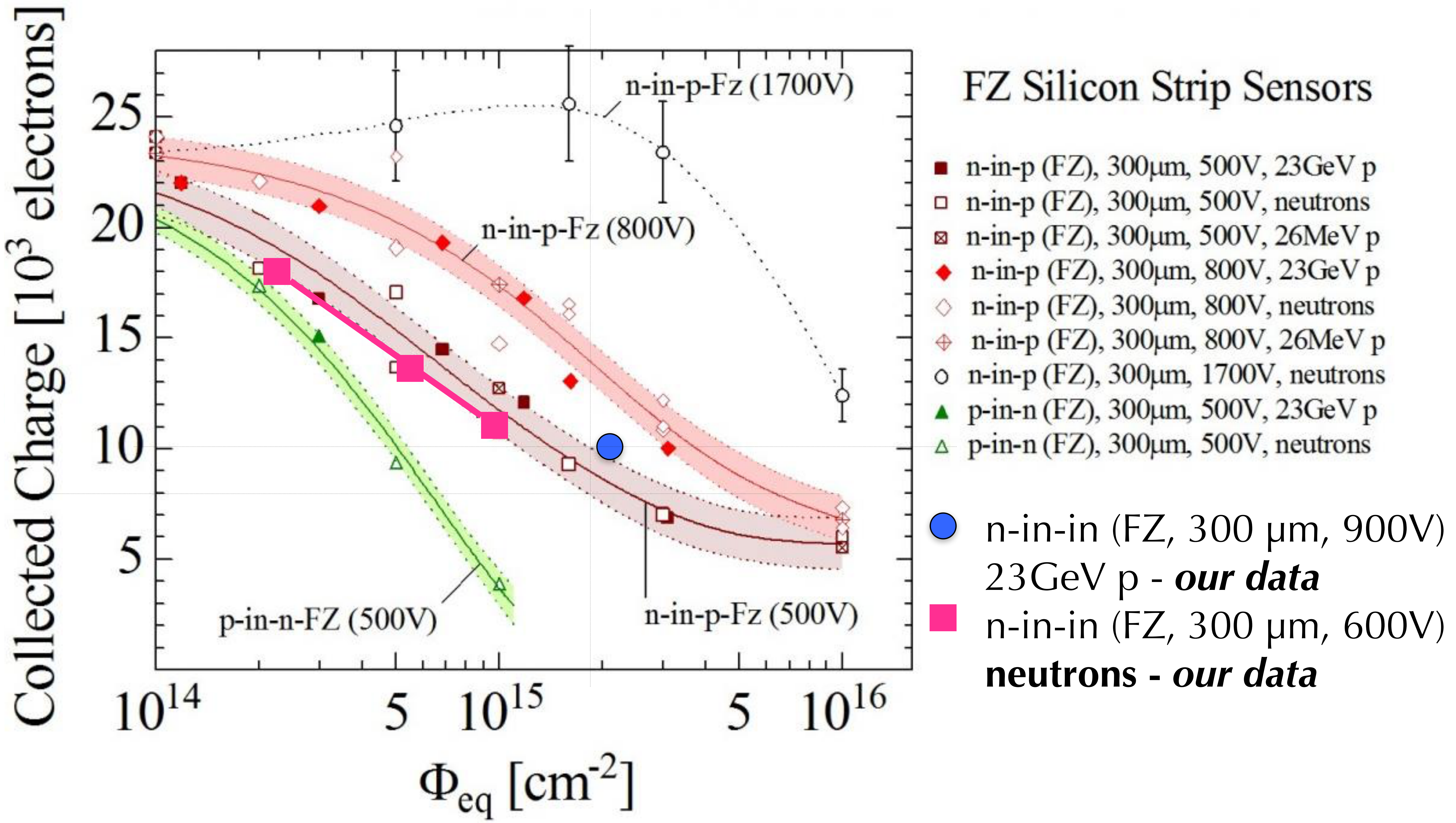
n+	→ 30 µm
gap	→ 7.5 µm
p+	→ 5 µm
gap	→ 7.5 µm
total	→ 50 µm

n+	→ 83 µm
gap	→ 6 µm
p+	→ 5 µm
gap	→ 6 µm
total	→ 100 µm

Collected charge vs Fluence

http://ph-news.web.cern.ch/content/rd50-radiation-tolerant-silicon-detectors-1





Results have been published in **NIM 2016 06, 020** and included in the Tracker **TDR**

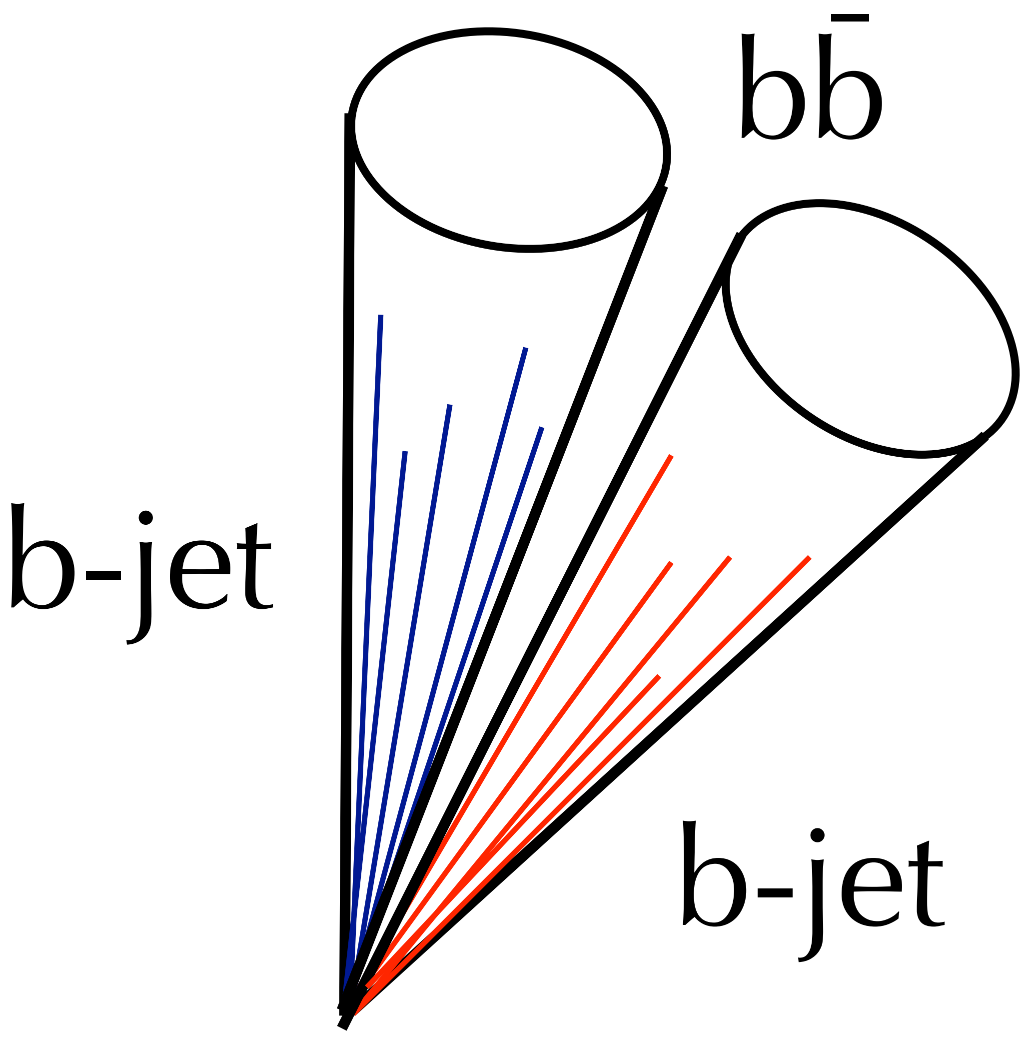
$H(b\bar{b})$

300 400 500 600 H p_T (GeV)

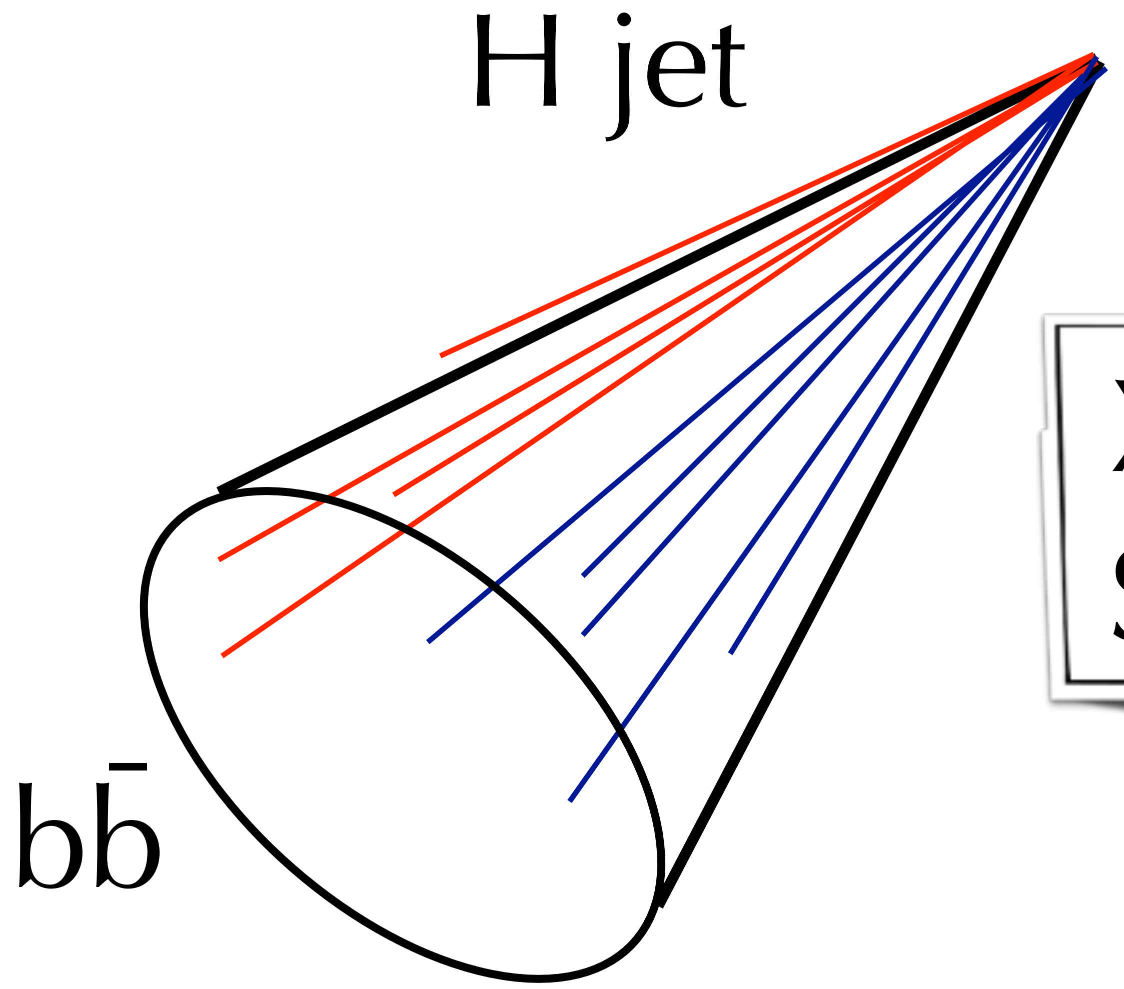
$dR(b\bar{b}) \sim 2m_H/p_T$

two-separated b-jets
(R = 0.4)

one single large-cone (fat) jet
(R = 0.8)



$VH(b\bar{b})$
VBF H
X→HH(4b)

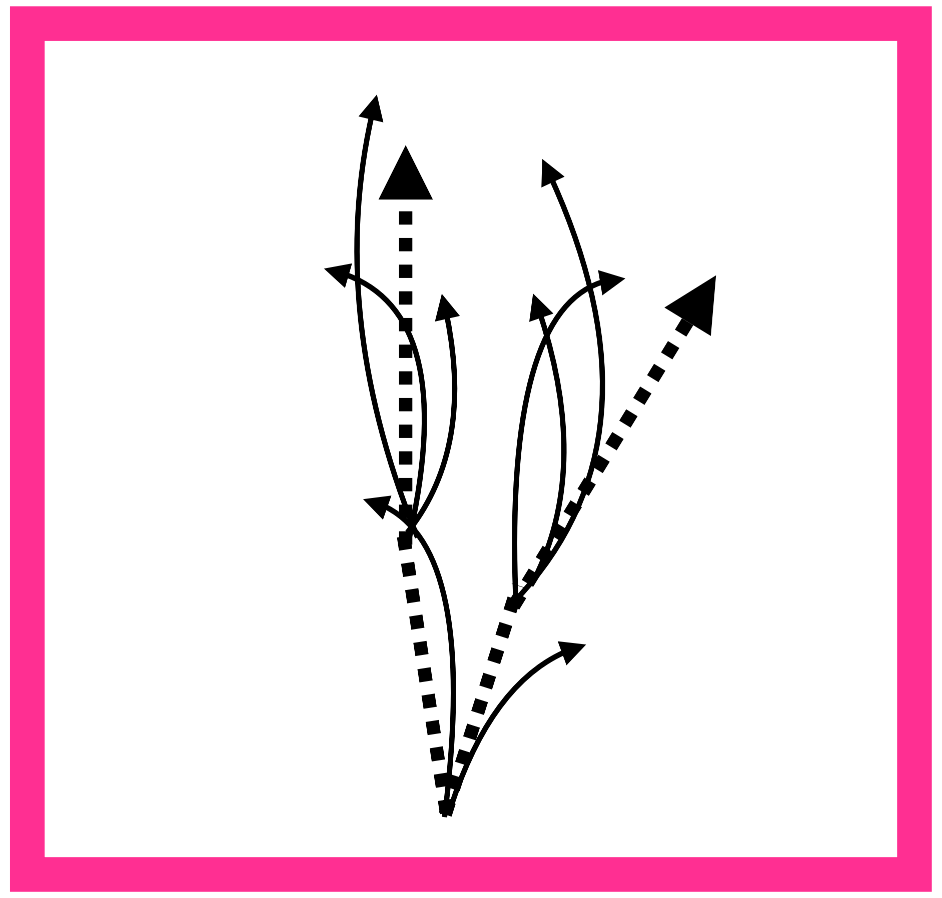


X→VH/HH
SM …

H($b\bar{b}$) tagging

The boosted H($b\bar{b}$) signal is identified as large cone size jets:

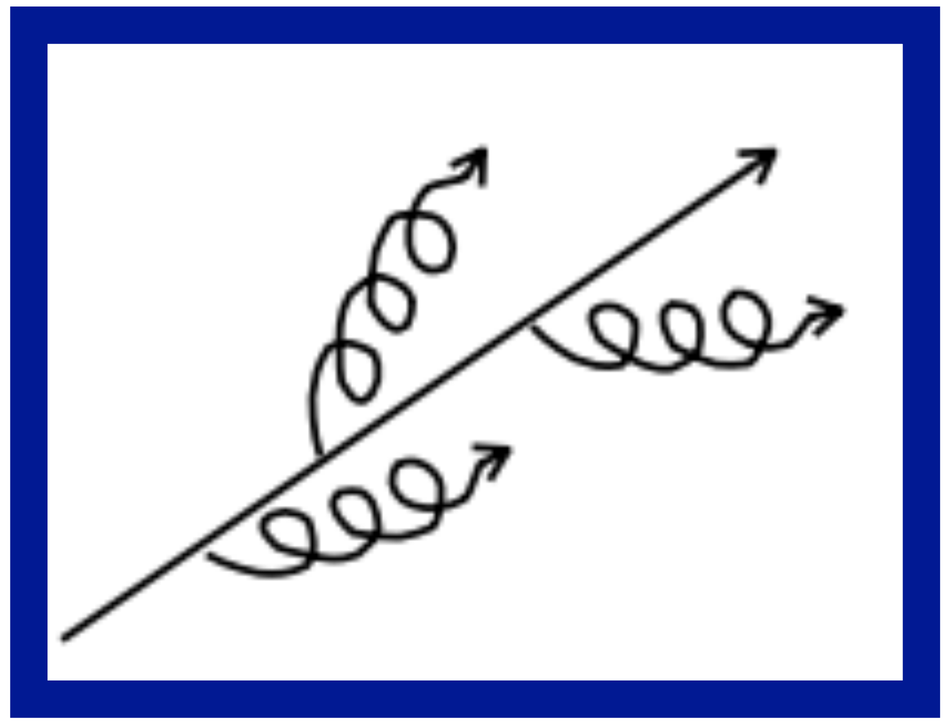
- R=0.8
- **PUPPI** (PileUp Per Particle Id) is used to mitigate **pile up effects**



H/Z($b\bar{b}$)

Our tools:

- **b-tagging** to reconstruct the two B hadrons from the b and $\bar{b}$ within the same fat jet
- jet **mass** compatibility with the Higgs
- the composite nature of the jet using **substructure**

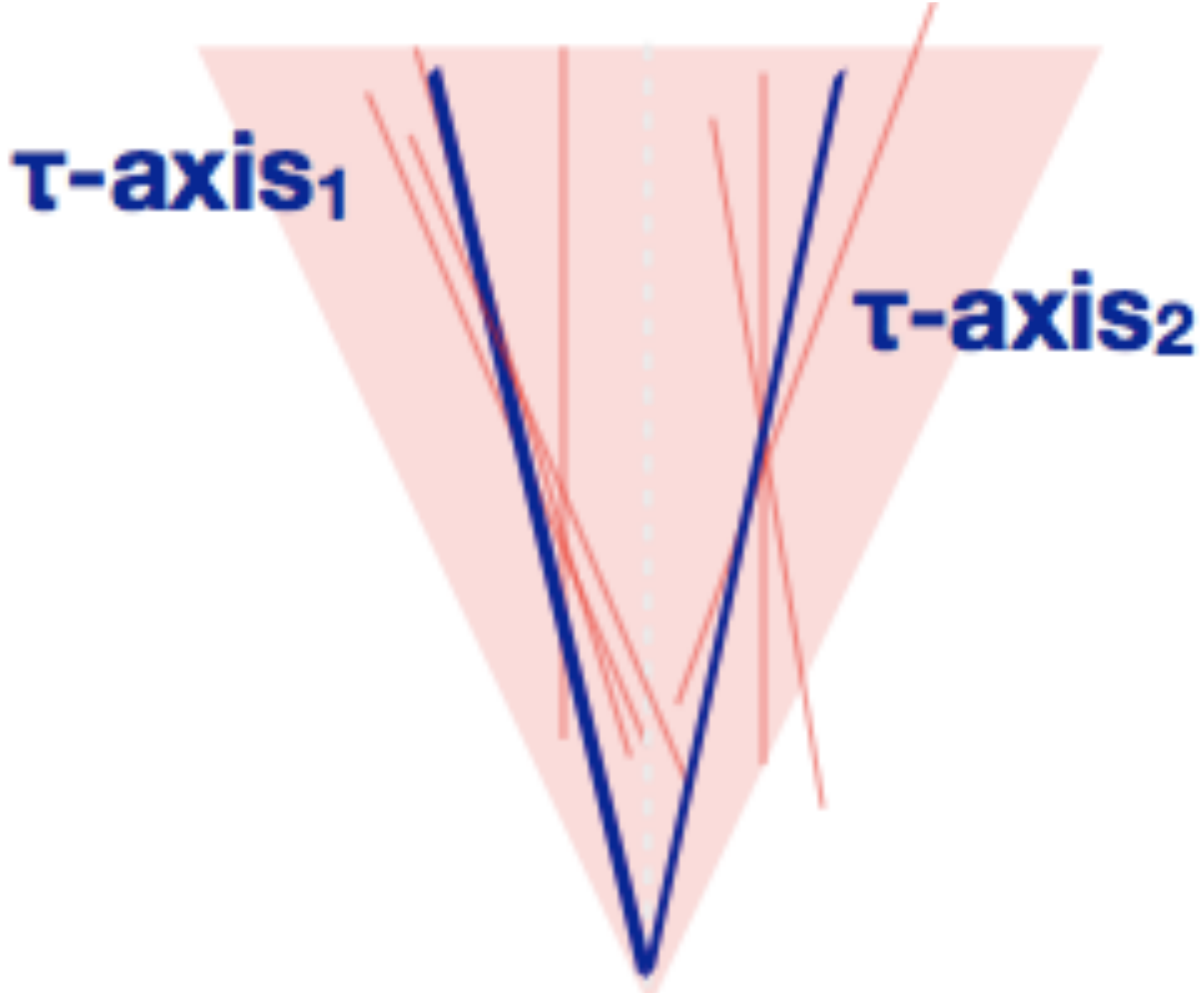


background q/g

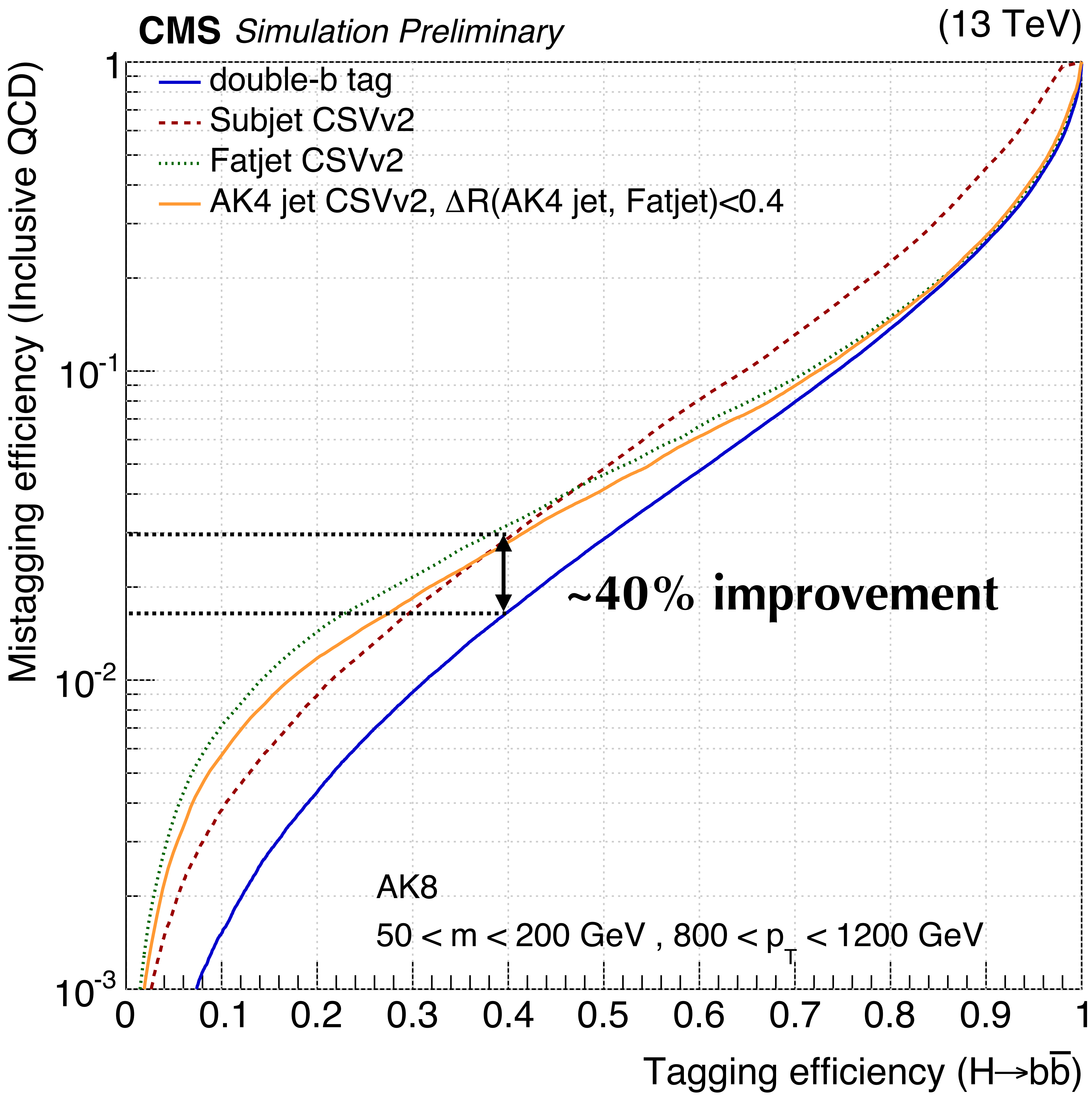
FNAL, Brown U, JHU
Rudjer B Inst, Hamburg U

CMS-PAS-BTV-16-002

double-b tagger



double-b tagger

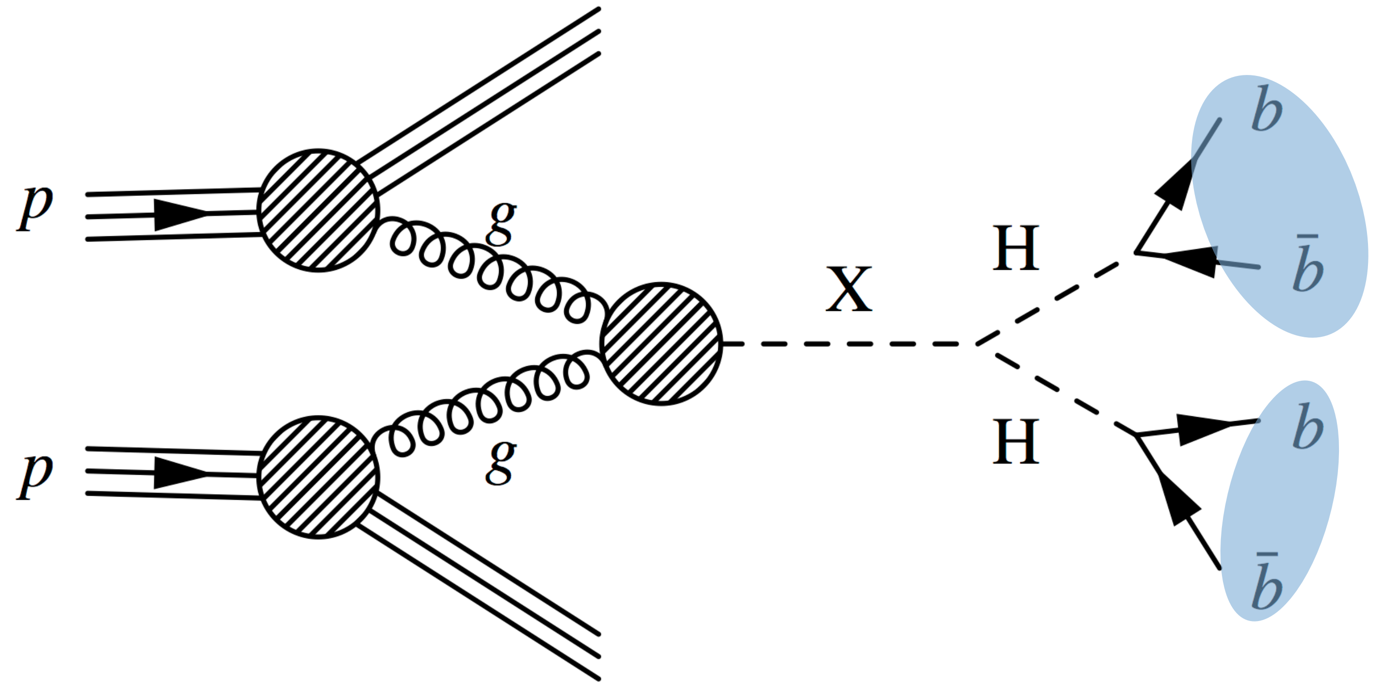


- Tool used in **HIG/B2G/EXO/SUS**

Machine learning approach is being investigated for 2017

Resonant Di-Higgs at CMS

FNAL, Florida U, JHU, Rutgers U, Colorado Boulder U, Kansas U



SM predicts an extremely low rate for hh production (30 fb at 13 TeV)

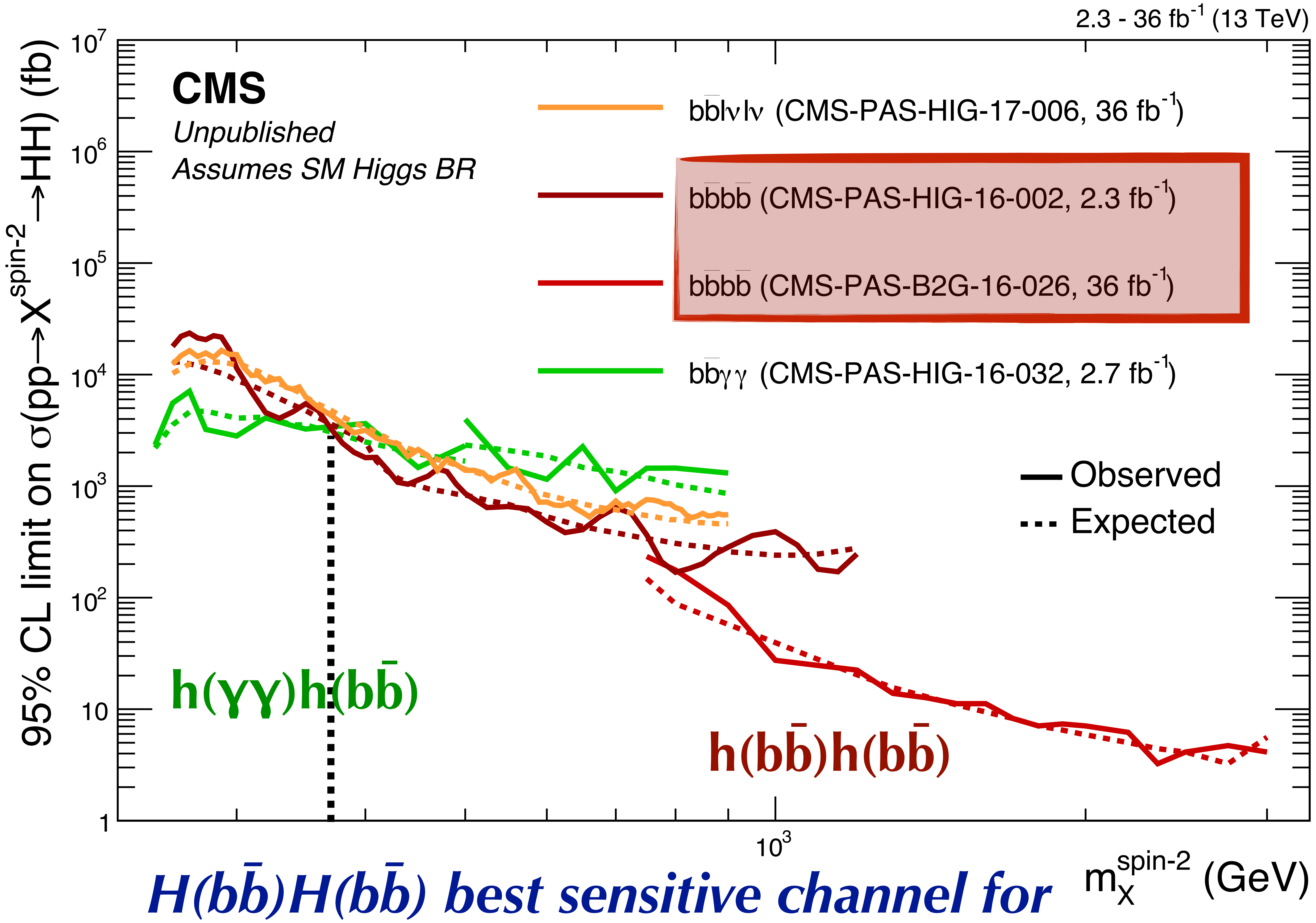
- 1000 times smaller than the single Higgs boson production

Significantly enhanced in many BSM scenarios

A natural choice is to exploit X→HH→ $b\bar{b}b\bar{b}$ (highest BR)

No significant excess in the range 1-3 TeV

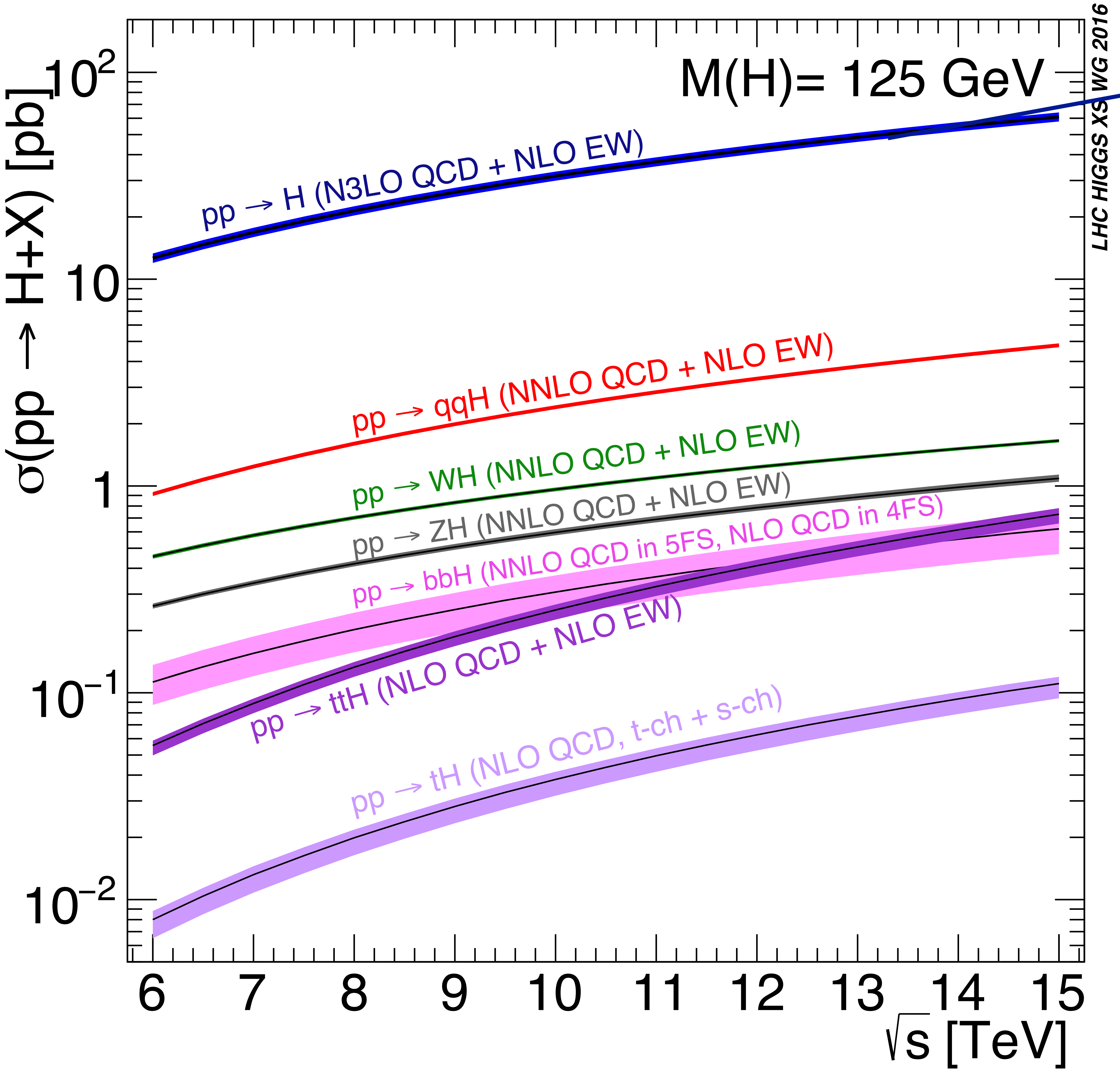
- Results are being published in **B2G-16-026** (just approved) and **HIG-17-009** (being approved)
- **Phase II studies for the TDR**

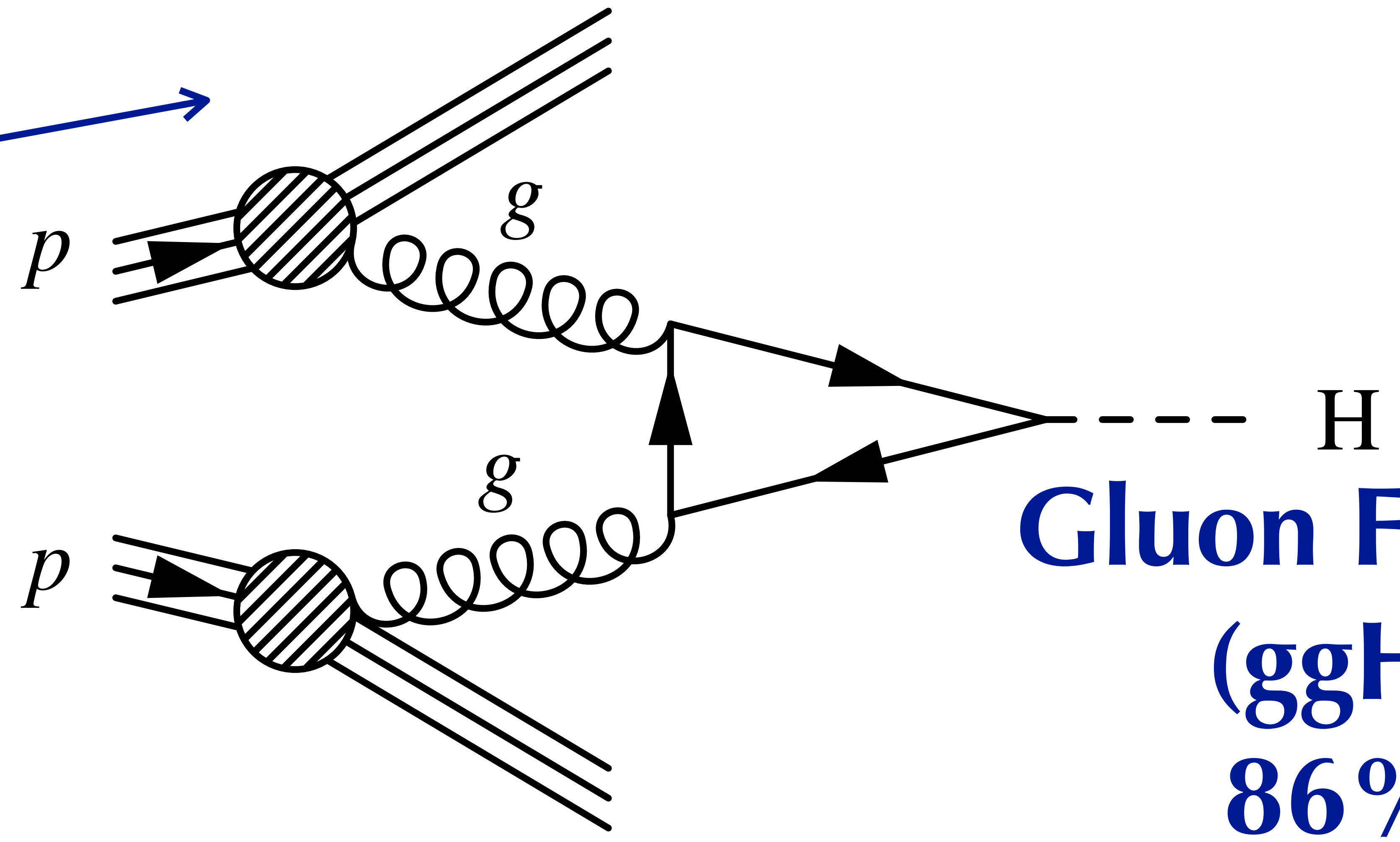


$H(b\bar{b})H(b\bar{b})$ best sensitive channel for heavy di-higgs resonances

Javier Duarte, Nhan Tran, **C.V. (FNAL),** Phil Harris (MIT), Cristina Suarez, Petar Maksimovic (JHU), Michael Krohn (Colorado Boulder U)

$H(b\bar{b})$ at LHC





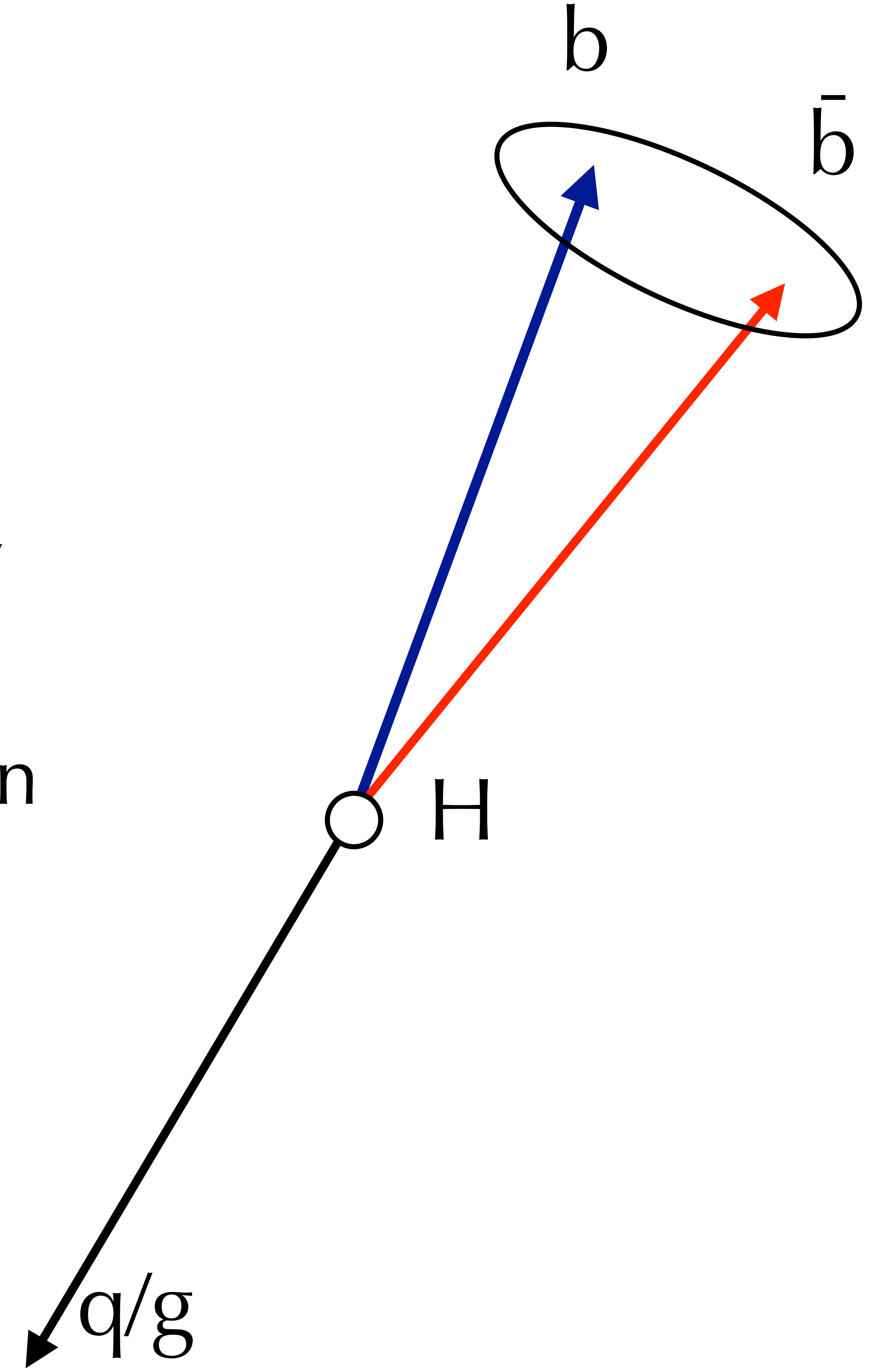
Gluon Fusion (ggH) 86%

- Two-jets final state
- Overwhelming background from QCD production of b quarks
  - 10^7 larger

Search for $gg \rightarrow H \rightarrow b\bar{b}$ historically **deemed impossible**

Search for inclusive H to $b\bar{b}$

- We can access this process in the **boosted dijet** topology
- Use initial state jet to get above the trigger threshold
- Look for boosted **H boson in a single jet mass** distribution
    - Use the **Z boson as Standard Model** candle
        - b-tagging to disentangle W/Z

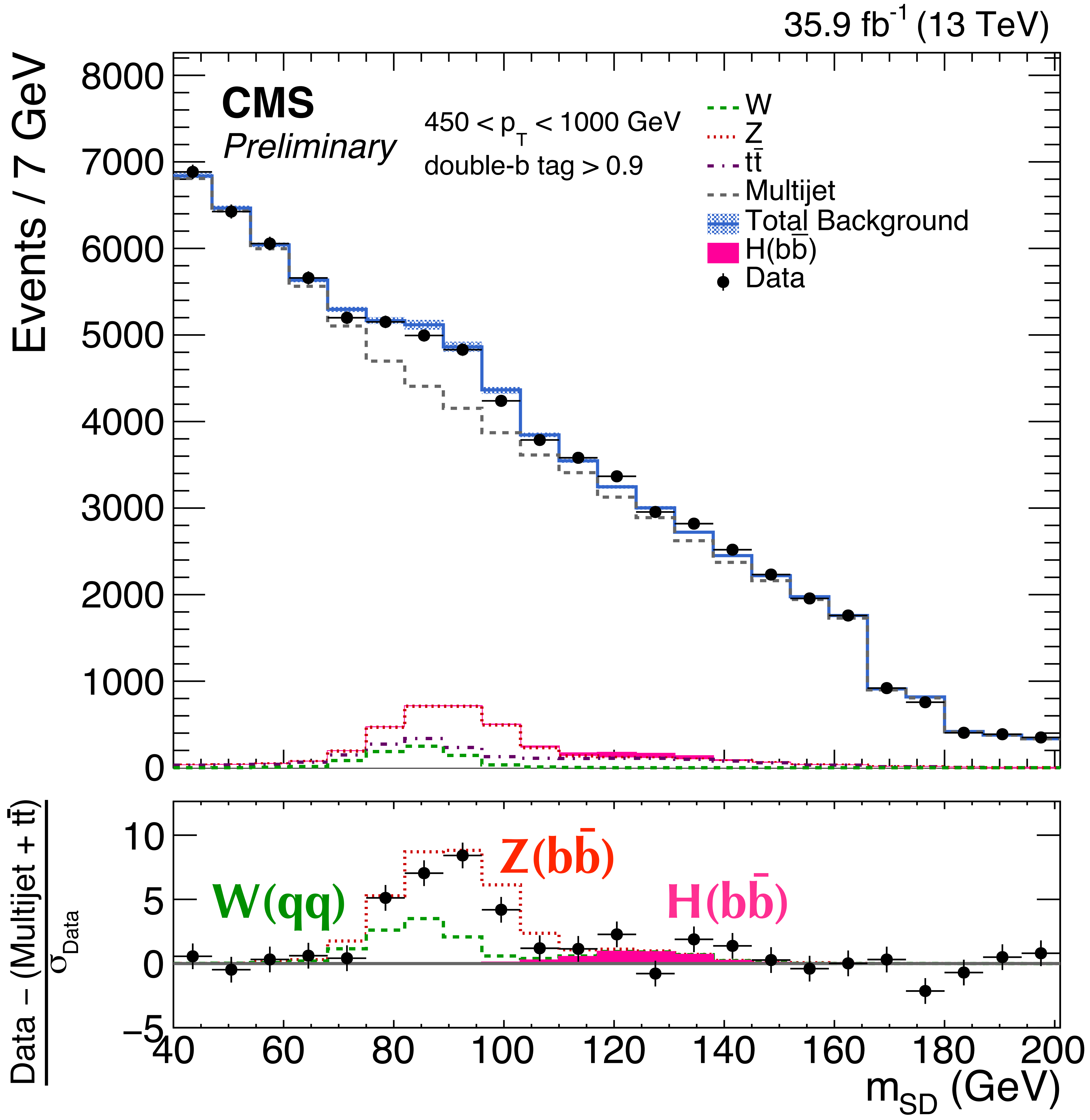


Simultaneous fit of the Z and H signals

- ***First Observation of the Z($b\bar{b}$) in the one-jet topology*** 5.1σ (5.8σ)
- The observed significance for the **H($b\bar{b}$)** is **1.5σ** (0.7σ)
- The measured **cross sections** for Z+jets and Higgs for jet p_T > 450 GeV are:

  σ_Z = 849 +155/-155 (stat.) +140/-205 (syst.)

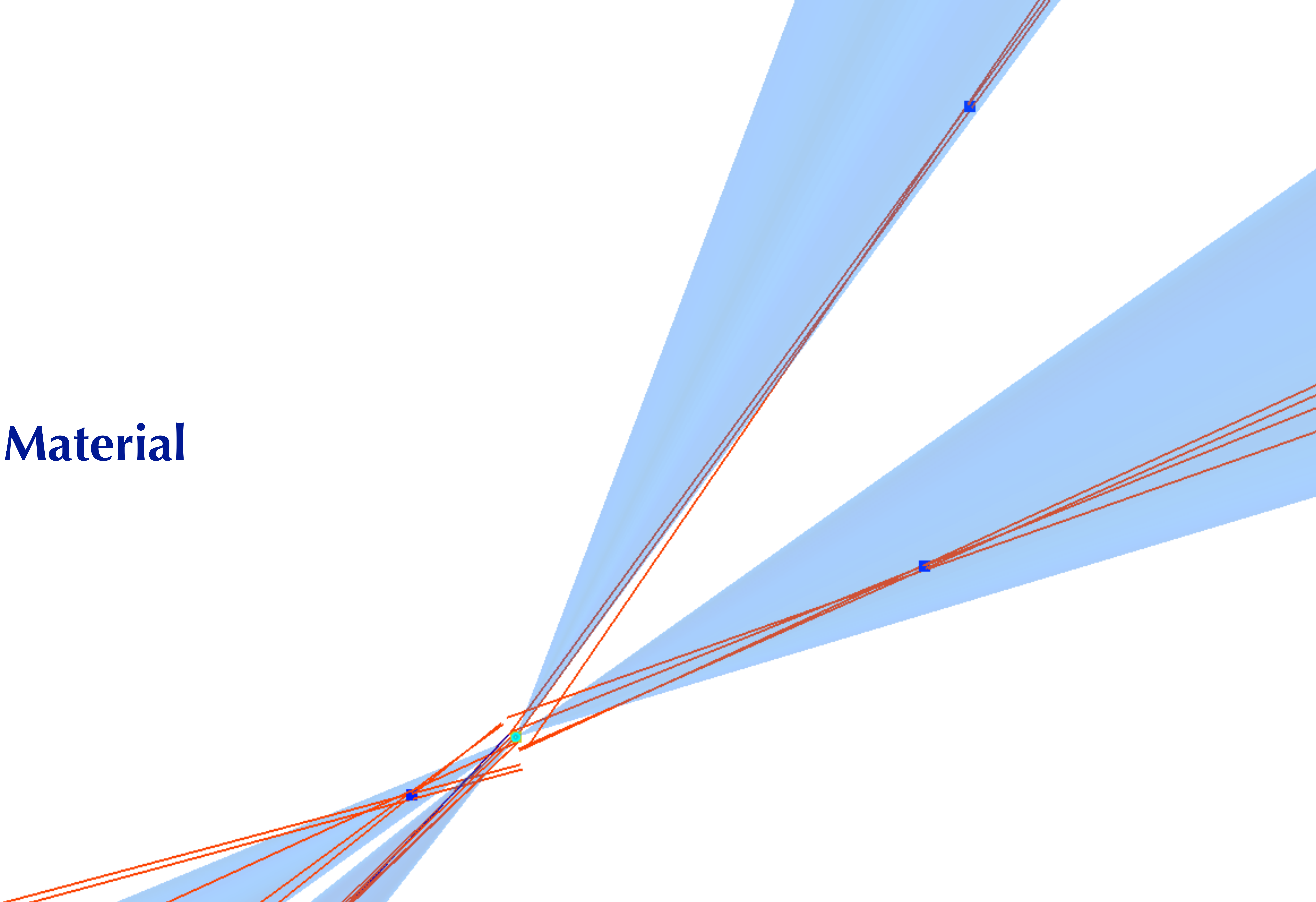
  σ_H = 74 +48/-48 (stat.) +10/-17 (syst.)



Summary

- Being at LPC allows one to effectively take part in an R&D program as well as have face-to-face discussions with local experts in physics object reconstruction, algorithms and other analyzers to improve the quality of the physics results
- The LPC effort of the Phase-2 pixels R&D has contributed to the CMS Tracker TDR
  - taking advantage of the Fermilab test beam facility and expertise
- Development of a new tagging approach is relying entirely on local expertise
  - continuing developing to make use of new deepNN techniques
  - local tutorials to build new expertise at LPC
- The most sensitive result on Dihiggs searches and the first search for inclusive Higgs boson decay to bb are mostly an LPC effort

Additional Material



ongoing R&D

Three different lines of the investigations for the inner parts of the pixel detector:

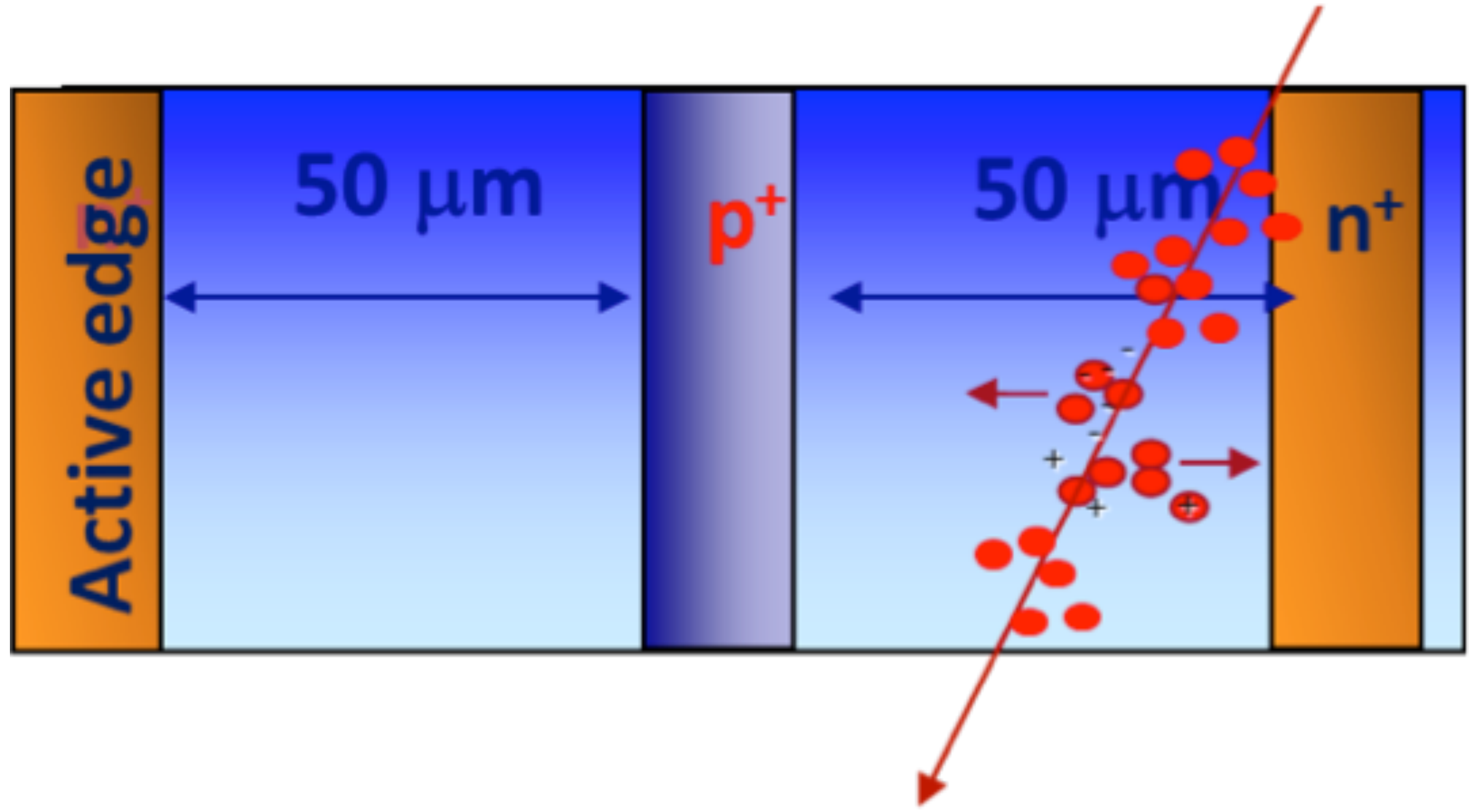
1. **planar pixel sensors in n-in-n**
2. **3D pixel sensors**
    - small pitch sensors investigated by CNM (Spain) and FBK/INFN (Italy)
    - thinner wafers (200 μm)
3. **thin planar pixel sensors in n-in-p**

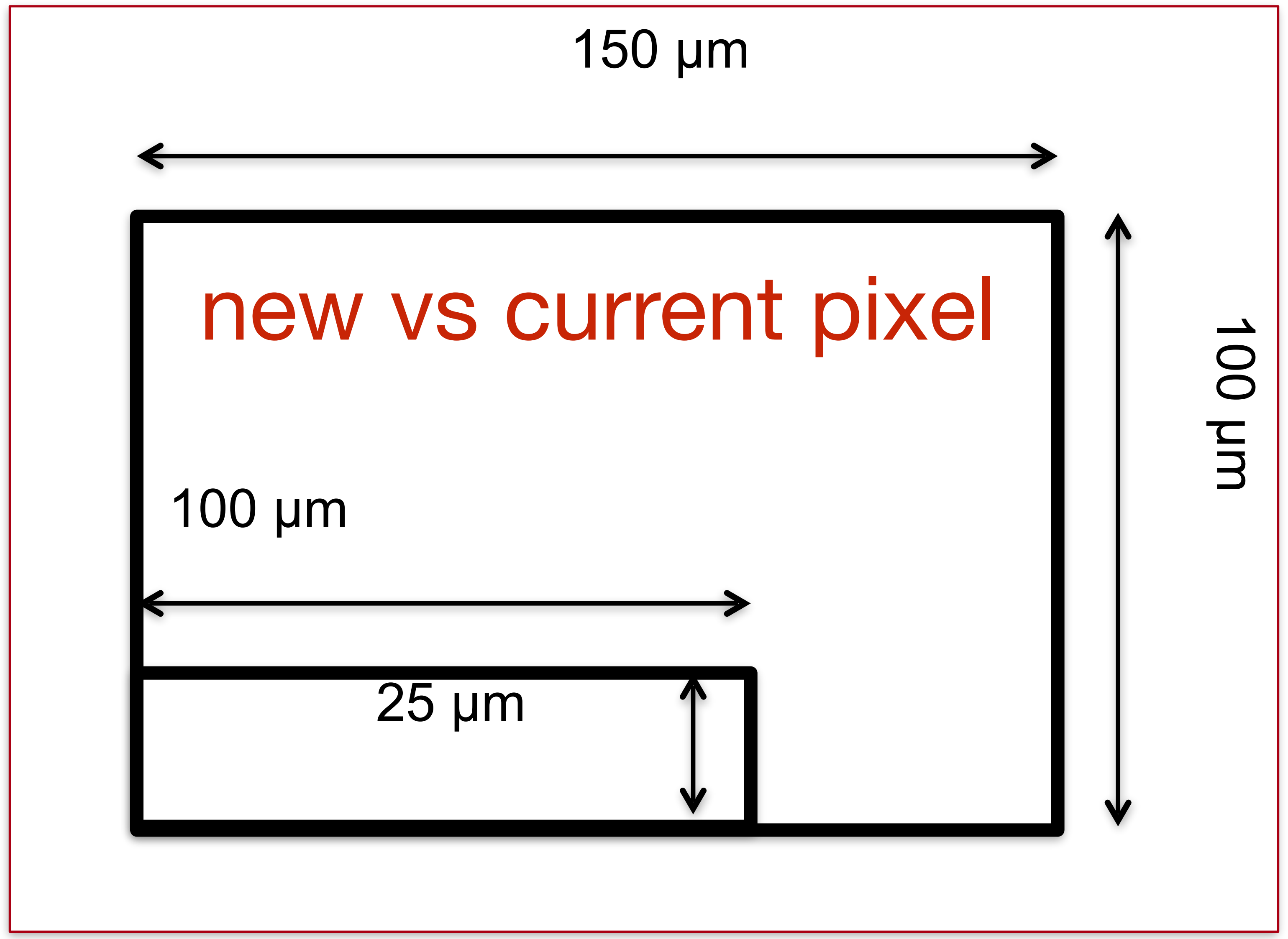
- **single sided** process favored
    - More vendors, **cost effective**
        - 6" n-in-p FZ with 150 μm thickness submission of small pitch pixel sensors
    - pixel sizes of 25μmx100μm and 50μmx50μm under investigations

Common advantages:

- Short drift path
- Higher field at same Vbias
- Lower operation voltage

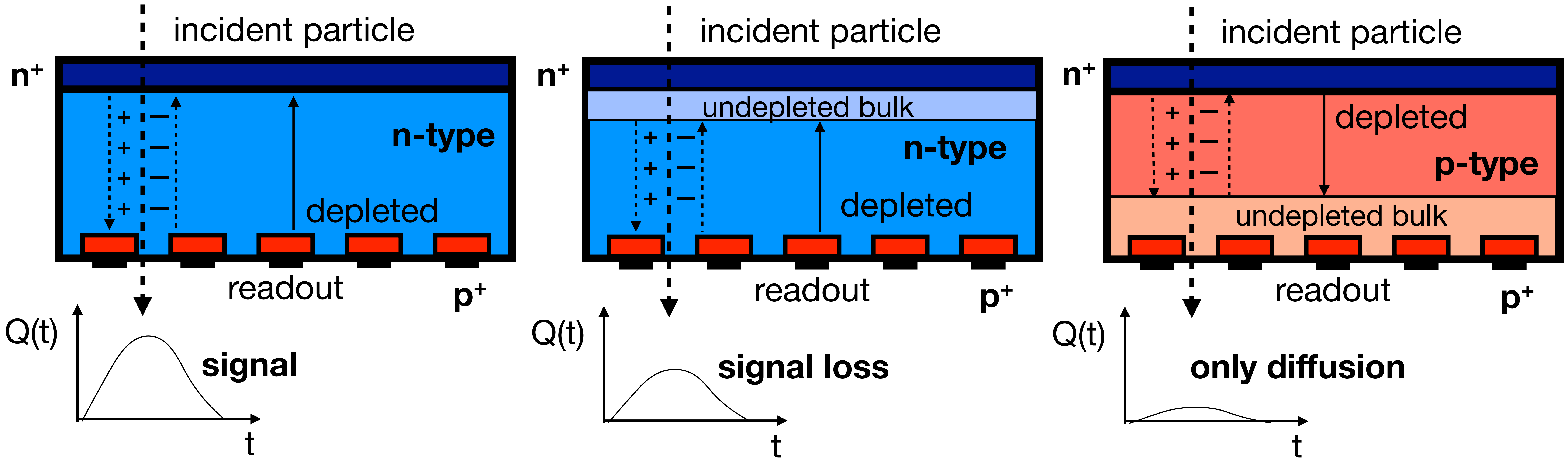
3D





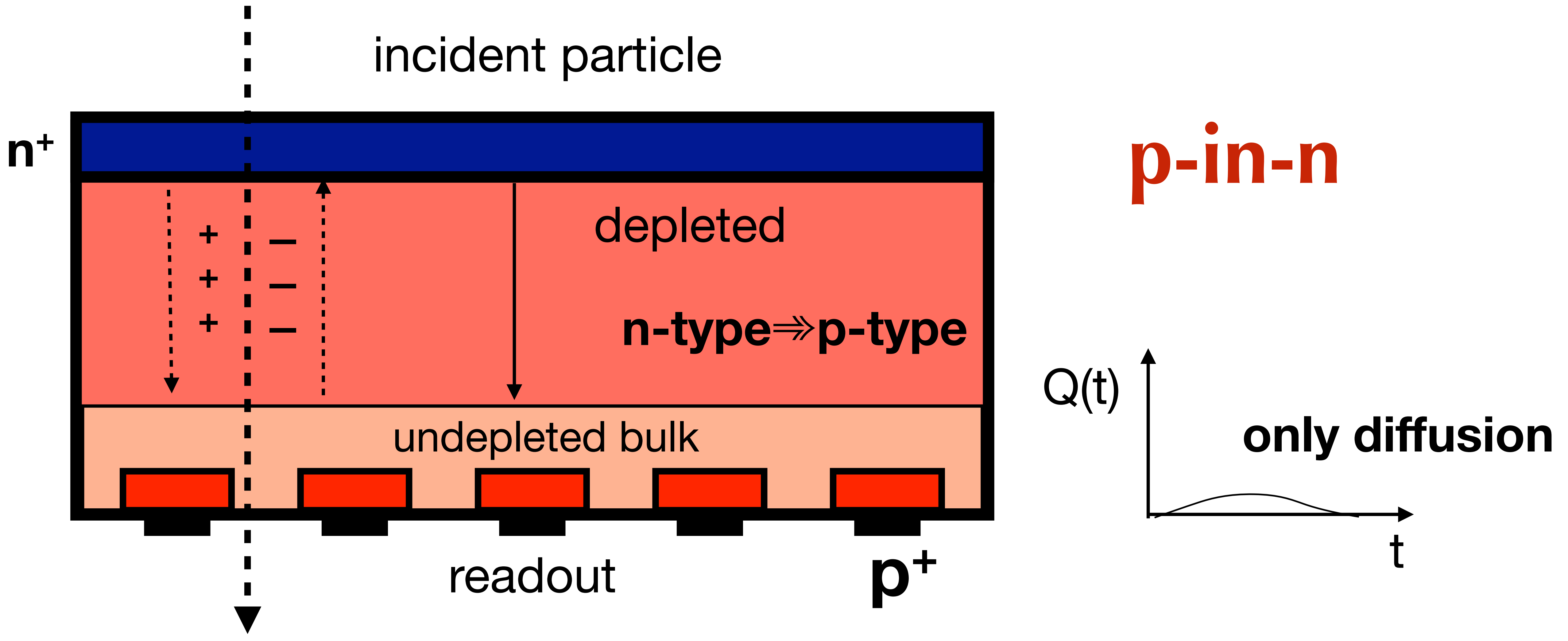
p-in-n

After irradiation (to a level implying type inversion) p-in-n does not function well if not fully depleted.



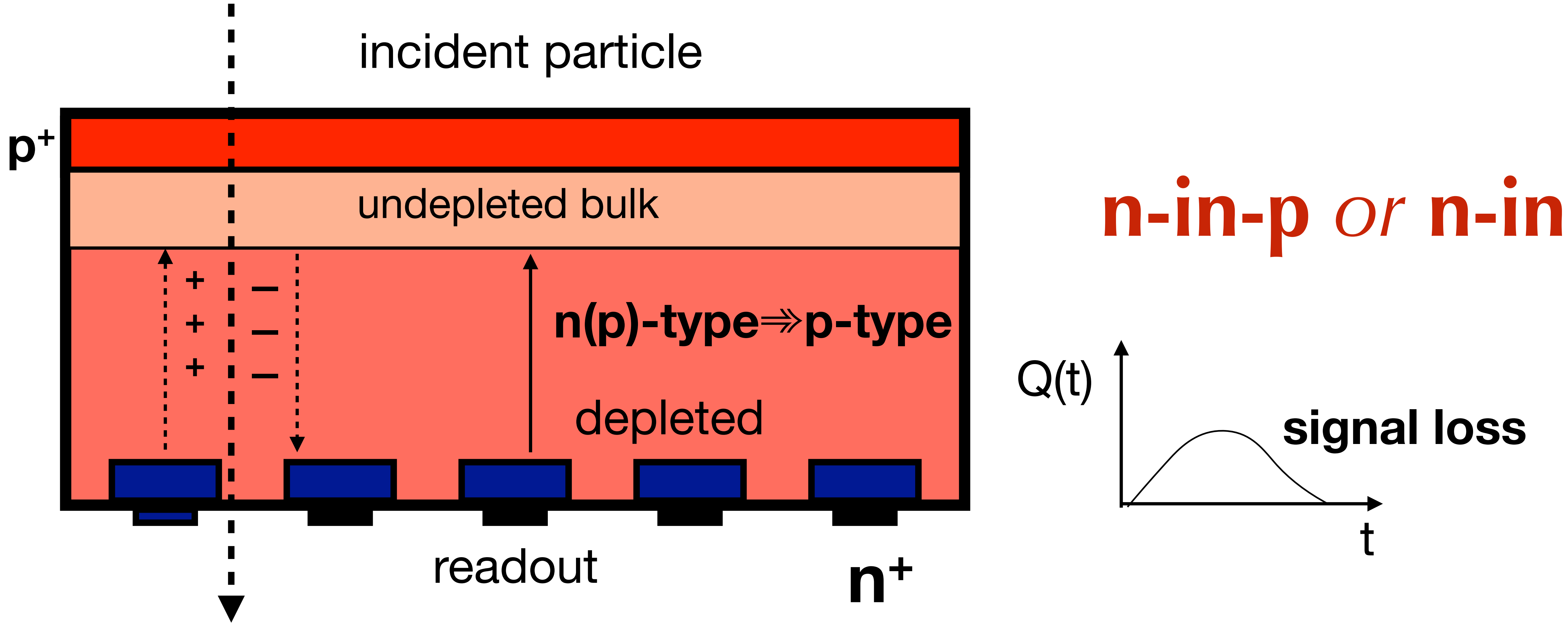
p-in-n vs. n-in-n

after irradiation and type-inversion



p-in-n

- signal loss
- resolution degradation due to charge spreading

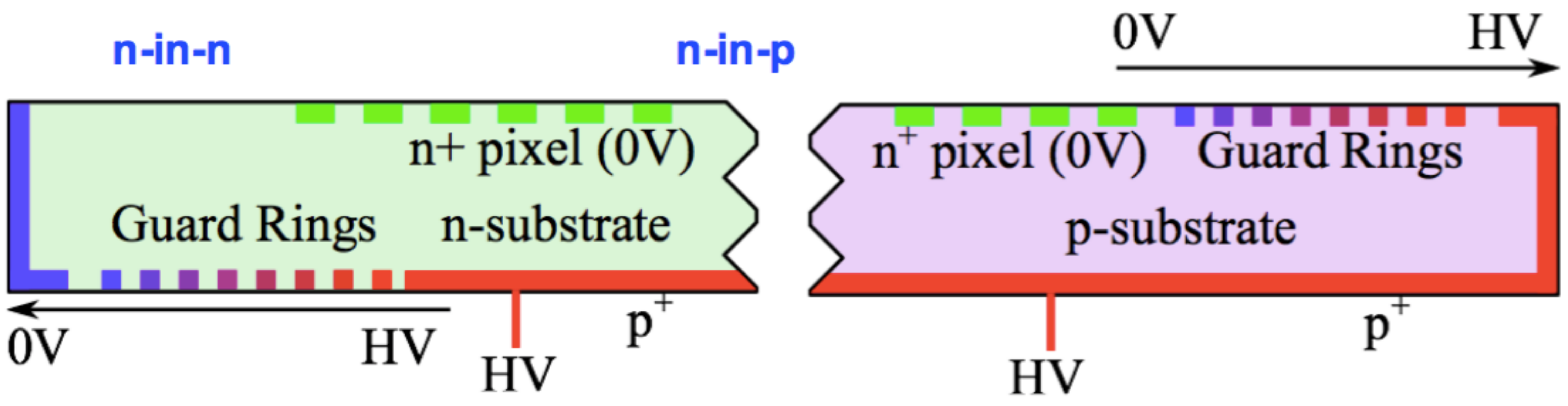


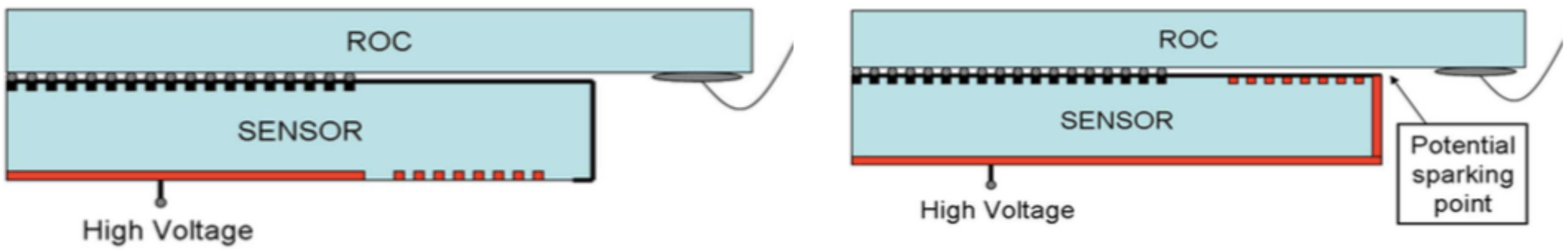
n-in-p *or* n-in-n

- faster charge collection (drift for electron is larger)
- CCE degradation

n-in-n vs n-in-p

double sided vs single sided





The Fermilab MTest beam facility

Fermilab Test Beam Facility provides **120 GeV protons** from Main Injector

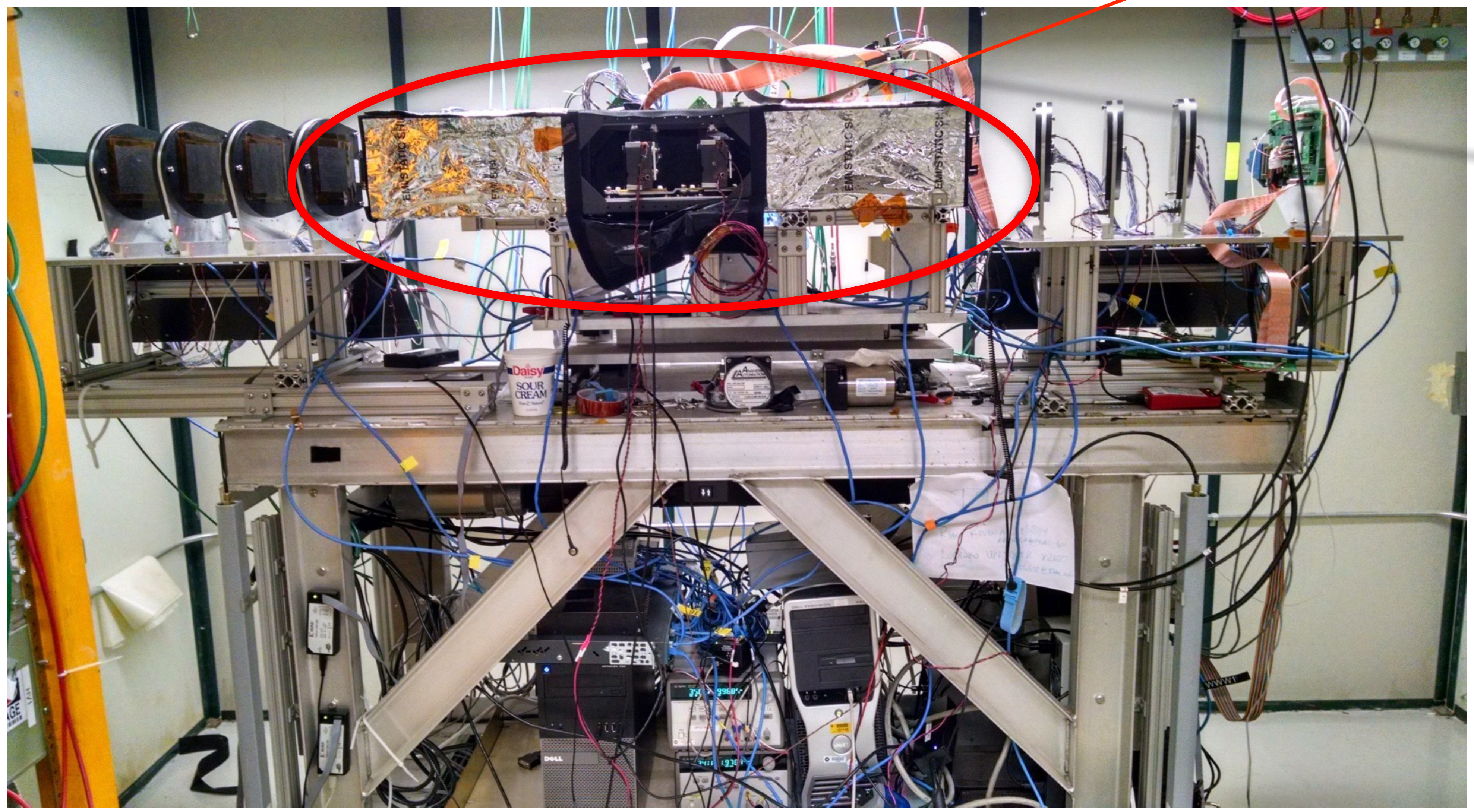
- At present 2 independent tracking telescopes are installed:
  - The legacy **pixel telescope** built using leftover CMS modules

    8 pixel planes

    readout based on PSI46 analog chip (Phase 0)

    (100x150 μm^2 pixel cell for 80 rows and 52 columns)

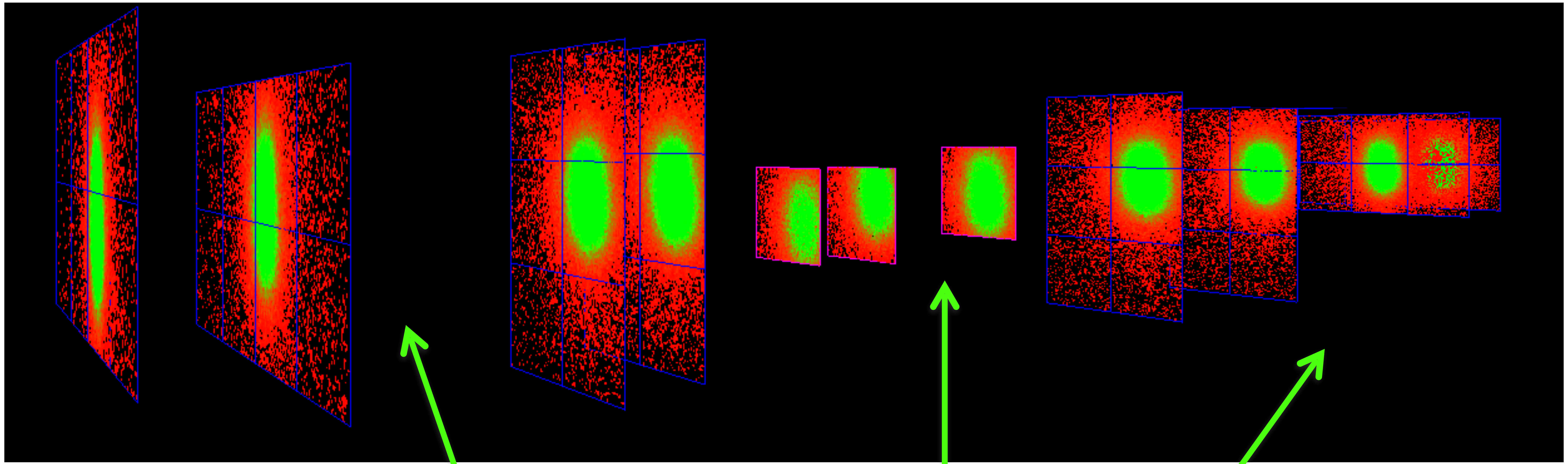
    ~8 µm resolution on each coordinate
  - The new strip based telescope (being commissioned now)



Pixel Telescope

NIM-A 811 (2016) 162-169

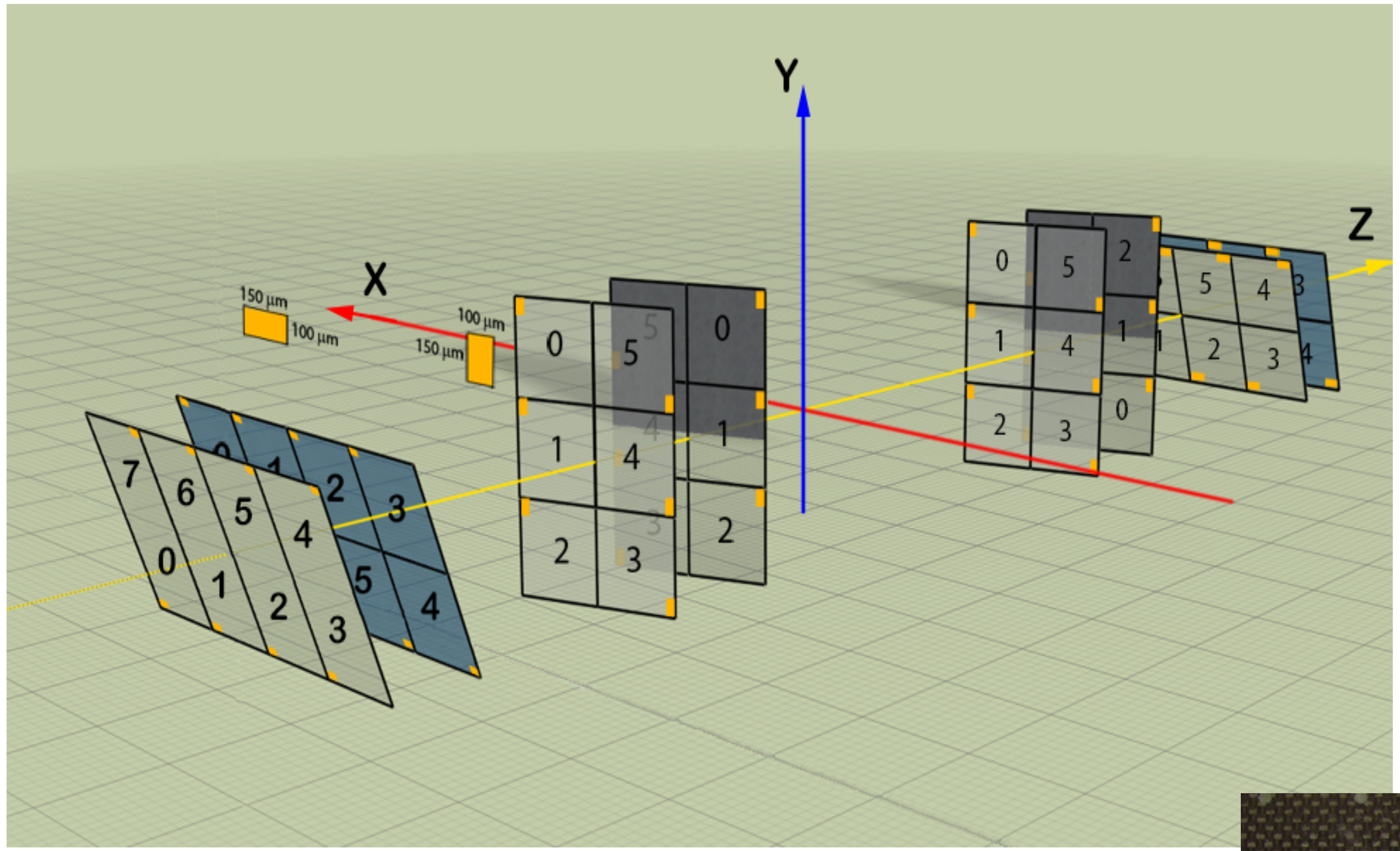
Online data taking

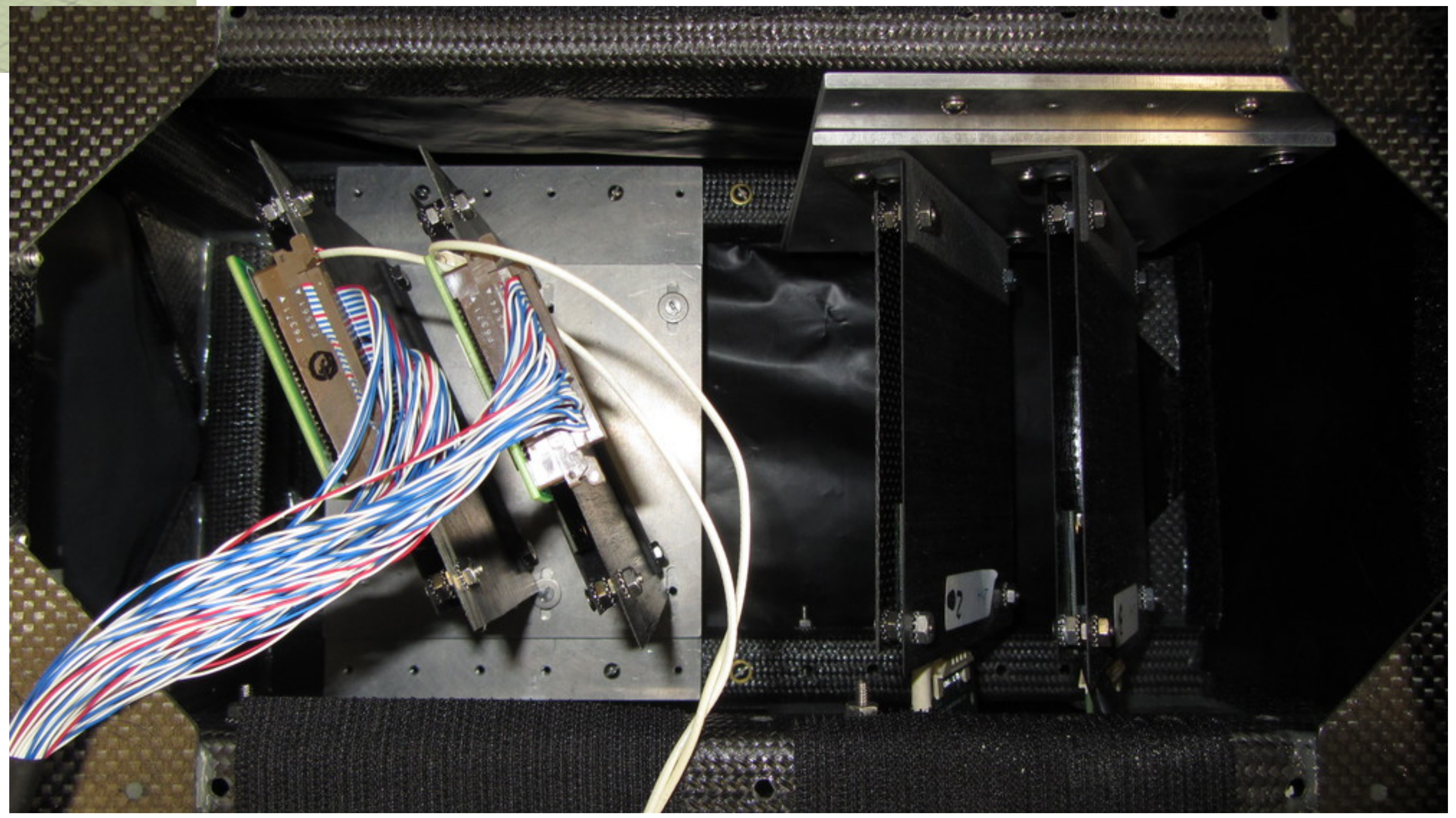


3 detectors under test

Pixel telescope

Pixel telescope planes

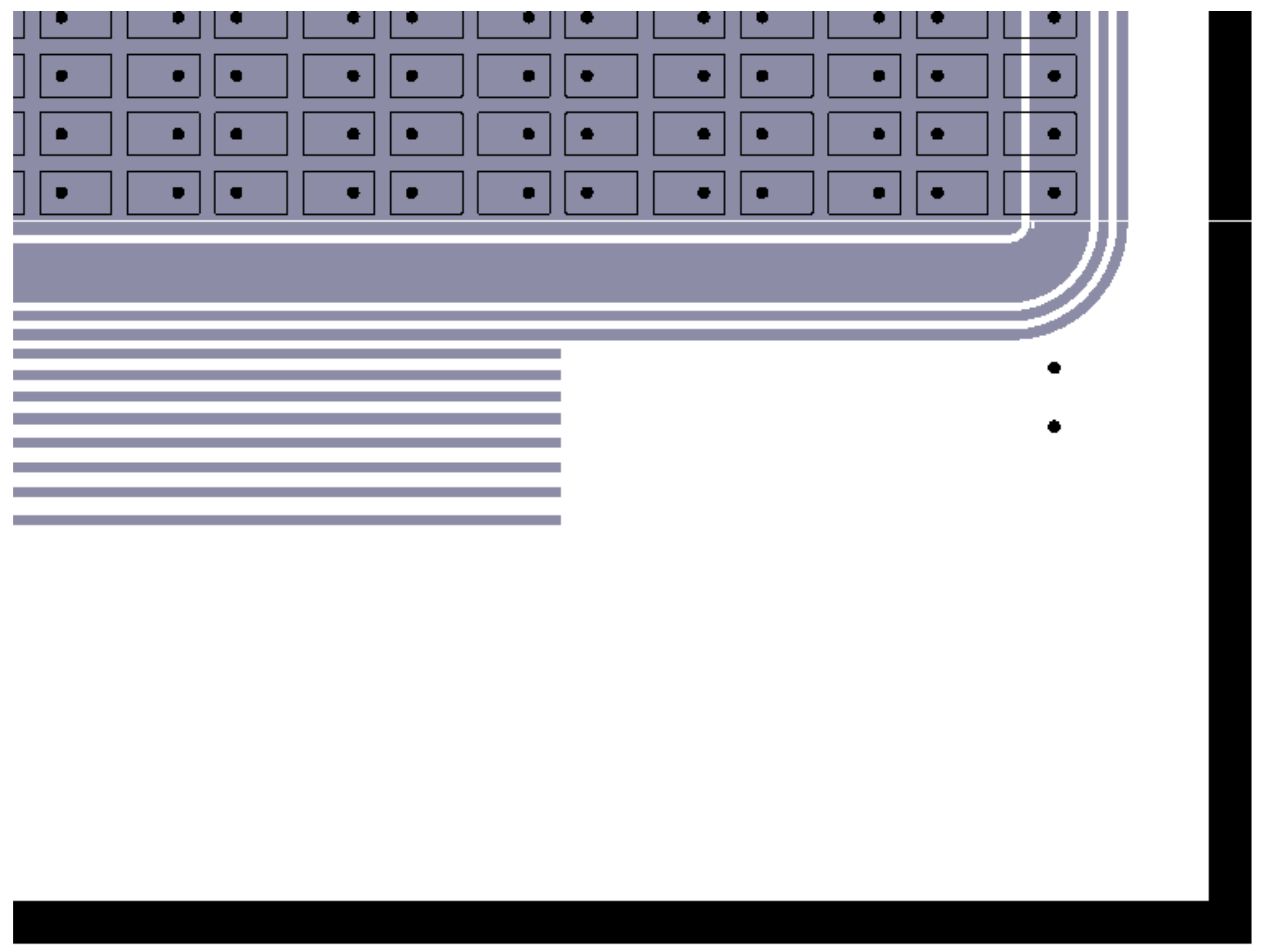


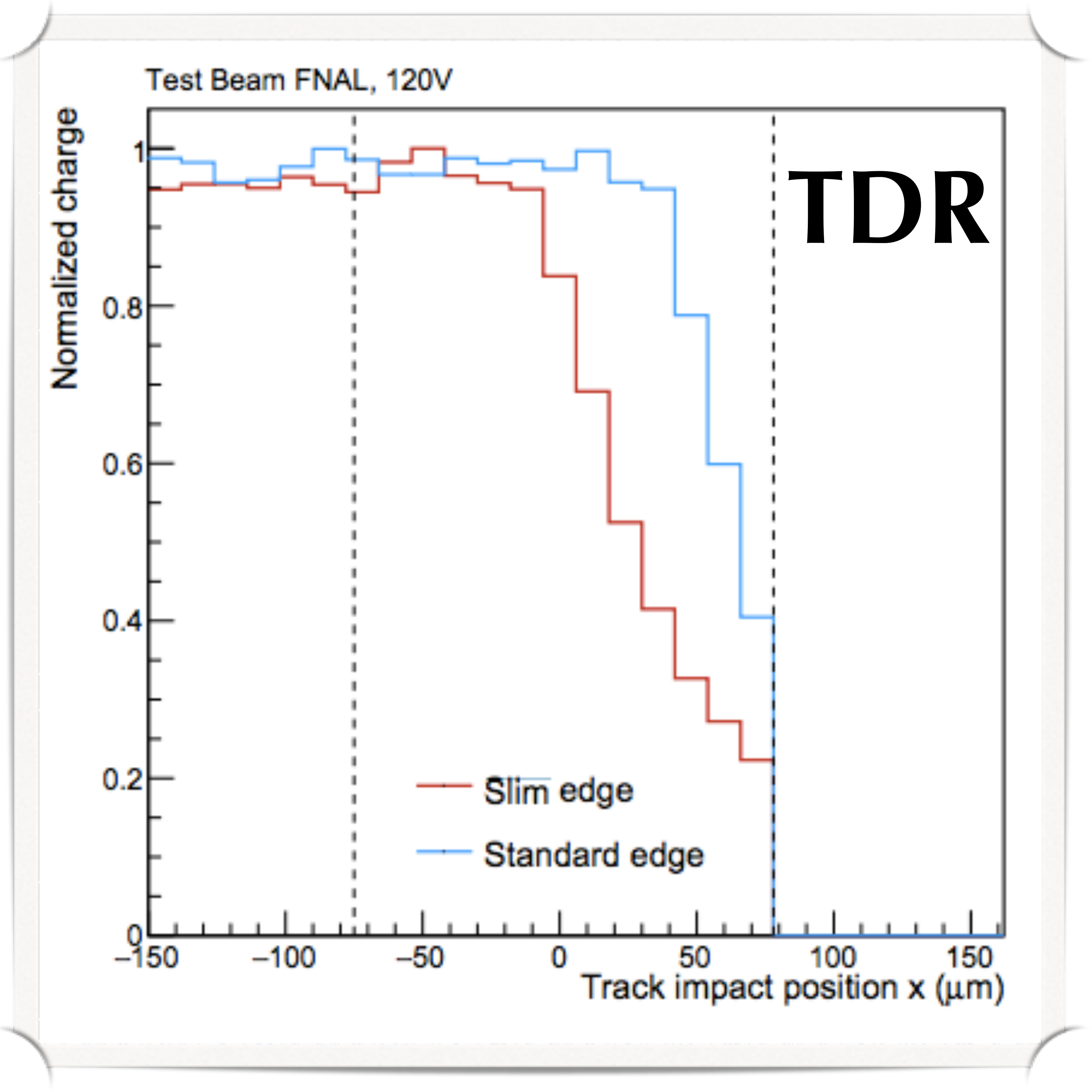


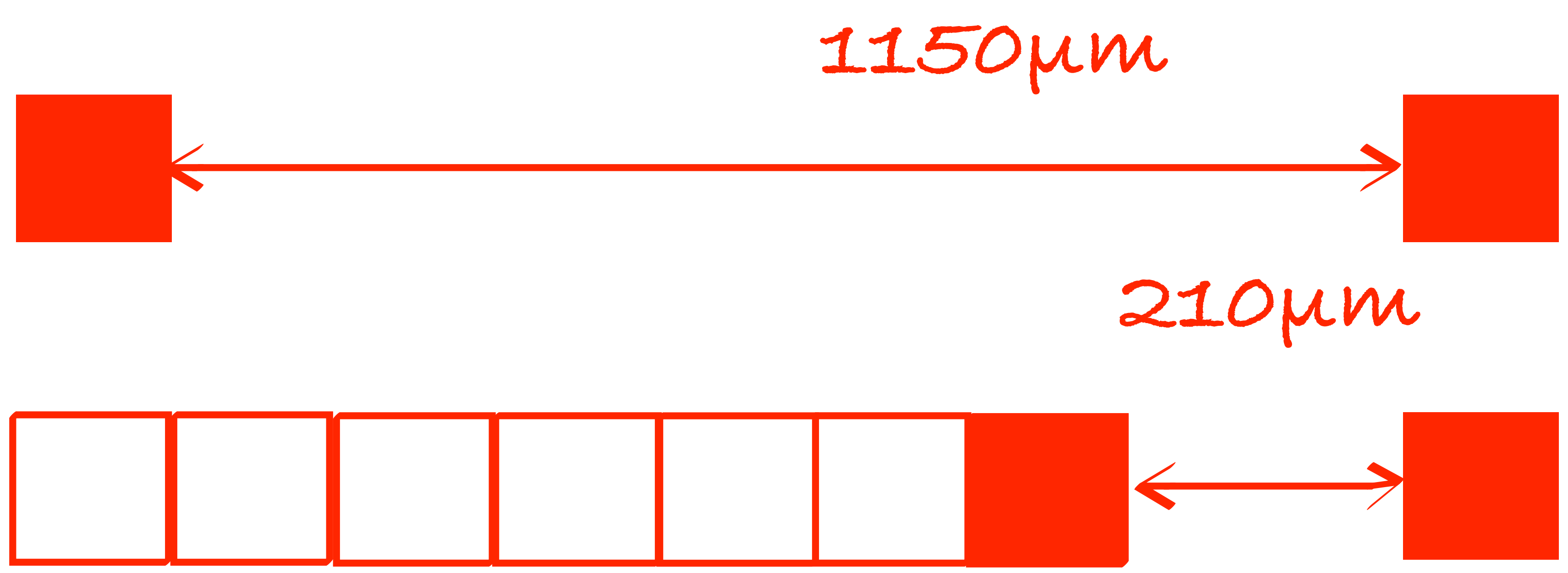
- 8 modules tilted at 25º to maximize charge sharing
- Coverage area only 1.6x1.6 cm^2
- Resolution on the detector under test of ~8 µm

Slim Edge

- Aim at minimizing the dead region at the physical edge of the sensor itself
- The efficiency of the pixels closely located to the edge depends on the geometry of the guard-rings on the opposite side (p-side).
- The pixel array (active area) normally ends at 1.15 mm from the dicing edge.
  - In these prototypes such distance has been reduced down to only 210 µm.
  - The reduction is of ~ 950 µm
- Loss of efficiency on the edge due to error on the track extrapolation
- Right and left edge behave similarly
- Slight worse efficiency for the Slim edge
  - effect on the last 15 µm, but 950 µm are gained (~6 pixels)

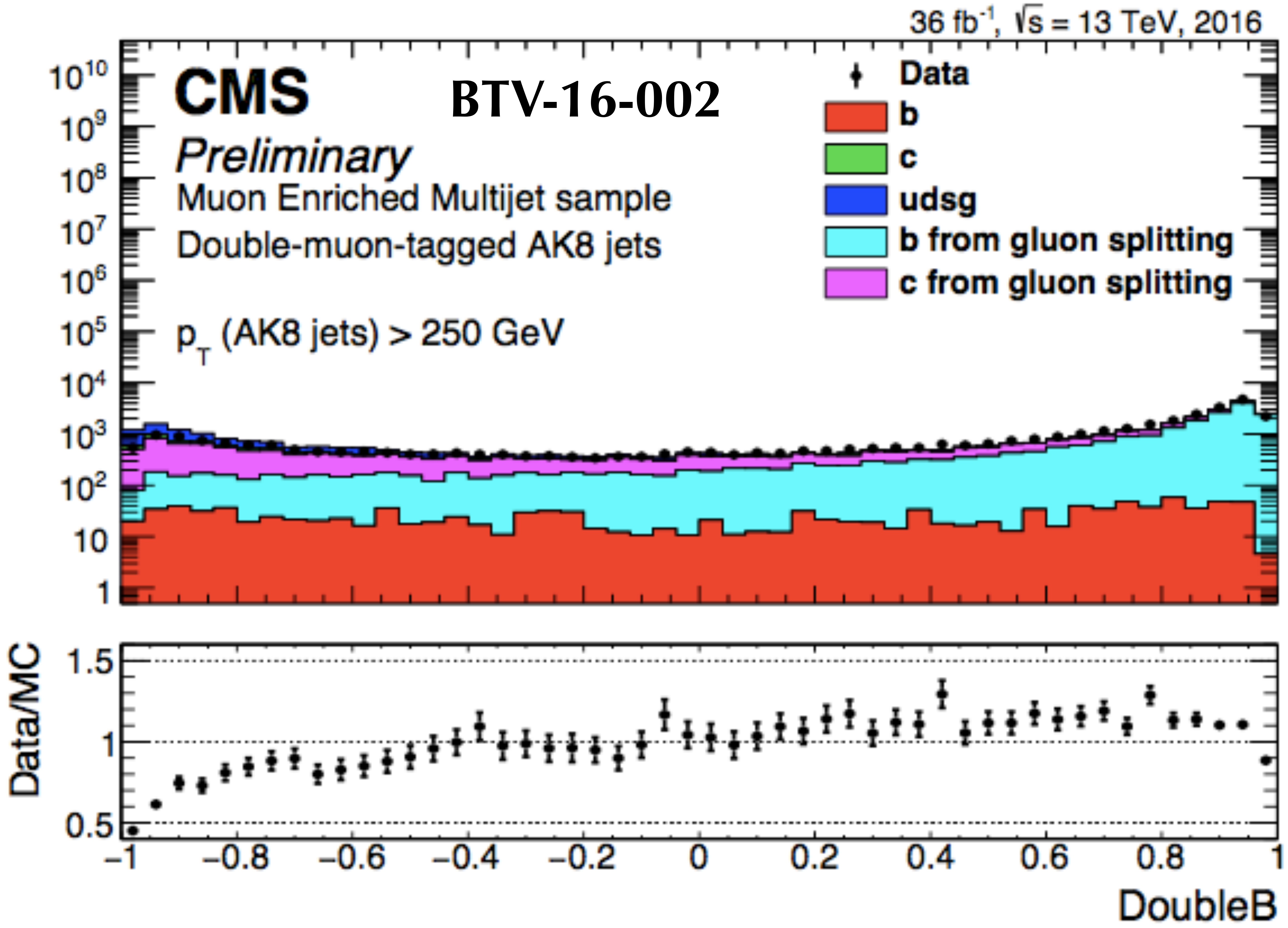






double-b Efficiency measurement in data

- Since there is no signal (yet!), and signal/background for Z($b\bar{b}$) is too small to measure now, we use:
  - g($b\bar{b}$) jets to measure the signal efficiency
- Event selection includes high p_T jet ($p_T > 300$ GeV), double-muon tagged jets, and a soft drop mass cut to ensure that g($b\bar{b}$) is in a phase space that is signal-like
- Measurement performed using 36/fb collected at 13 TeV (2016)
  - single jet triggers with thresholds such that we are 99% efficient for jet $p_T > 300$ GeV



The Higgs boson

LHC Run I legacy

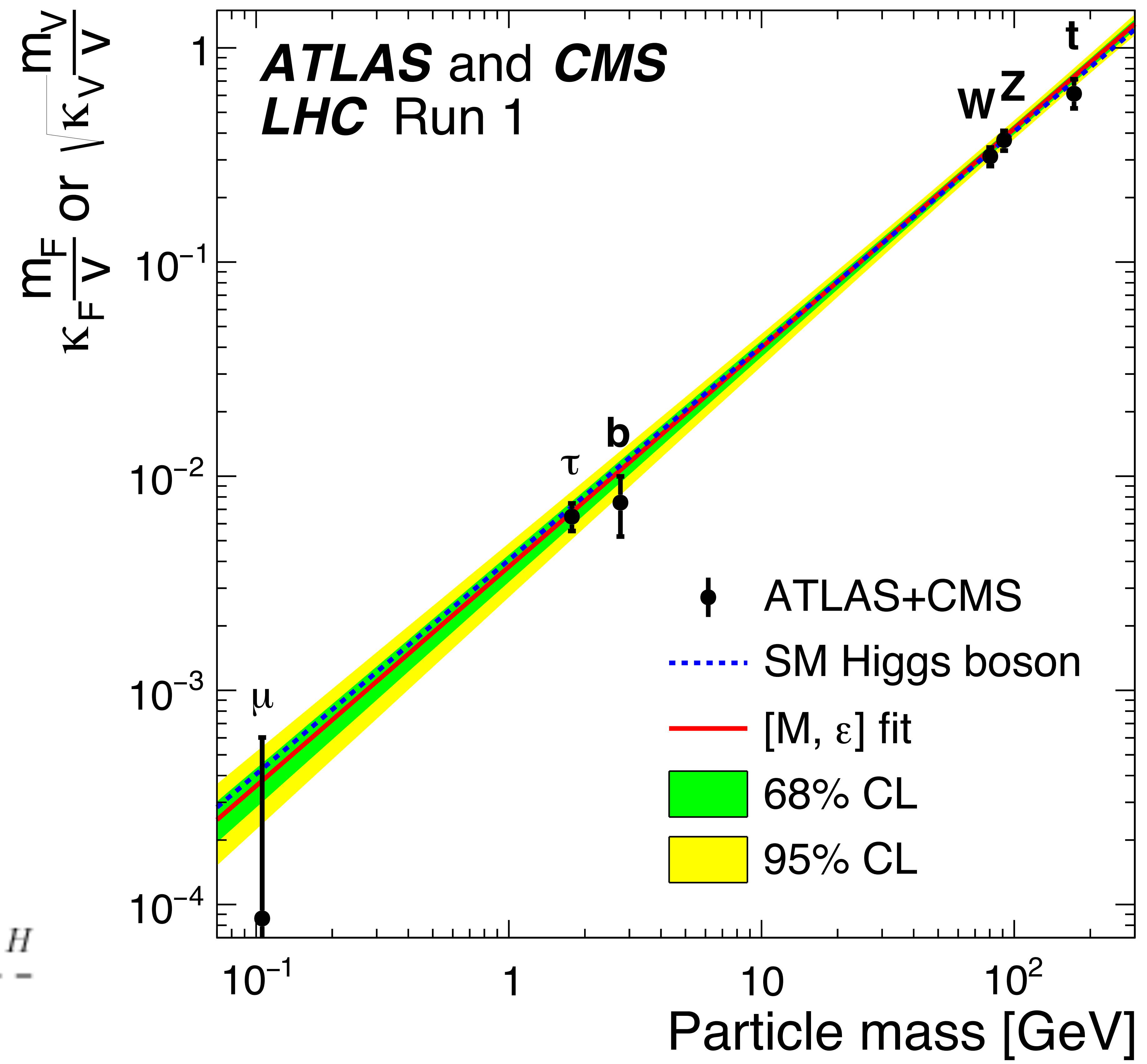
H $J^P = 0^+$

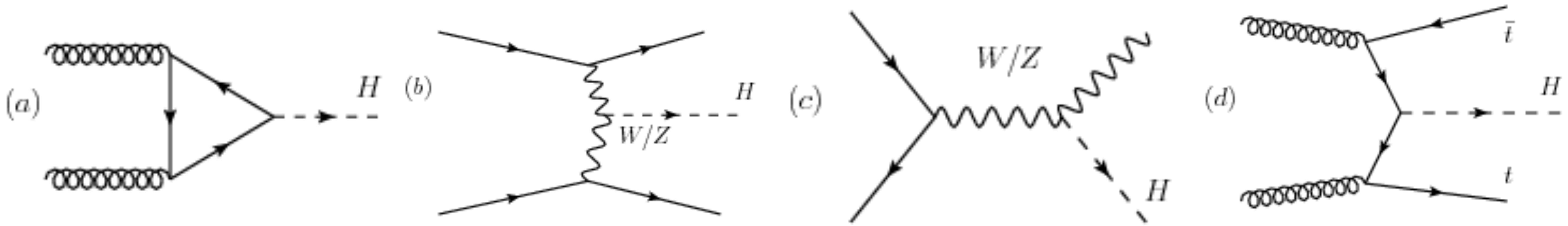
$m_H = 125.09 \pm 0.24$ GeV

observed production and decay rates are consistent with a SM Higgs boson within uncertainties

- 1st indication of the $H(b\bar{b})$ decay at LHC (2.6σ)
  - largest BR for SM H (~58%), dominates total width

JHEP08(2016)045



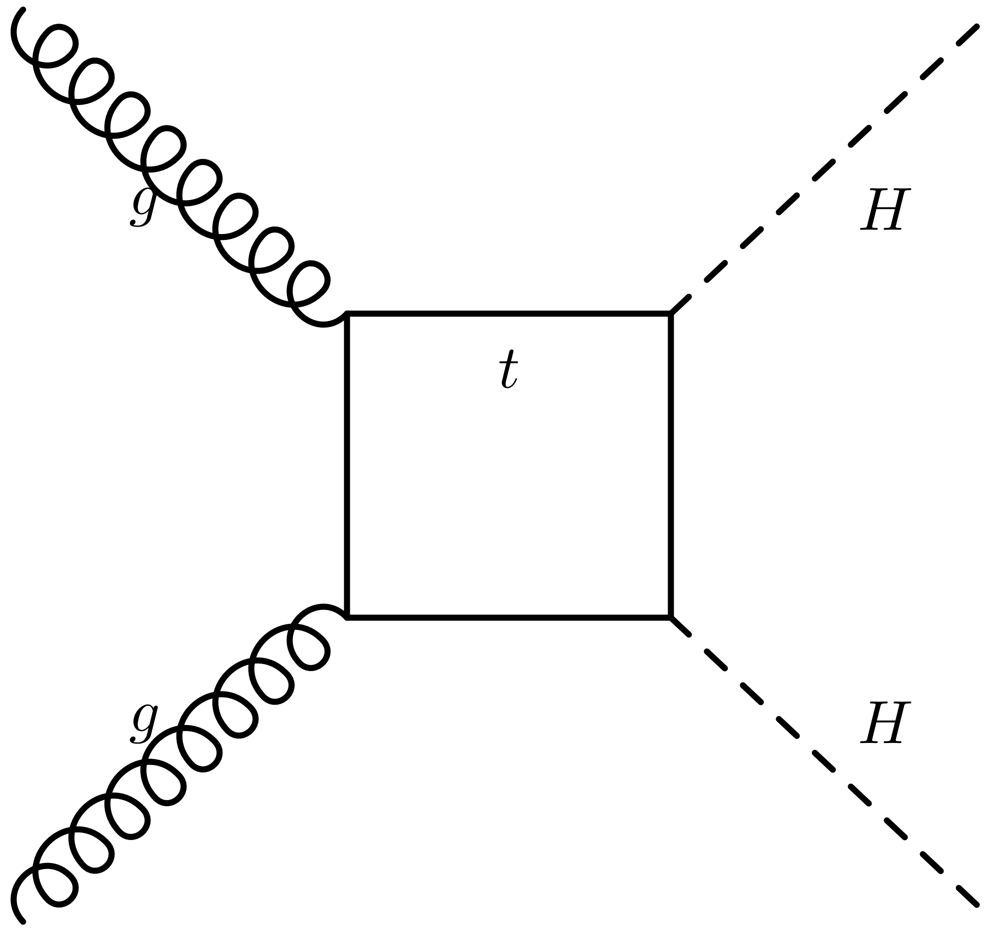


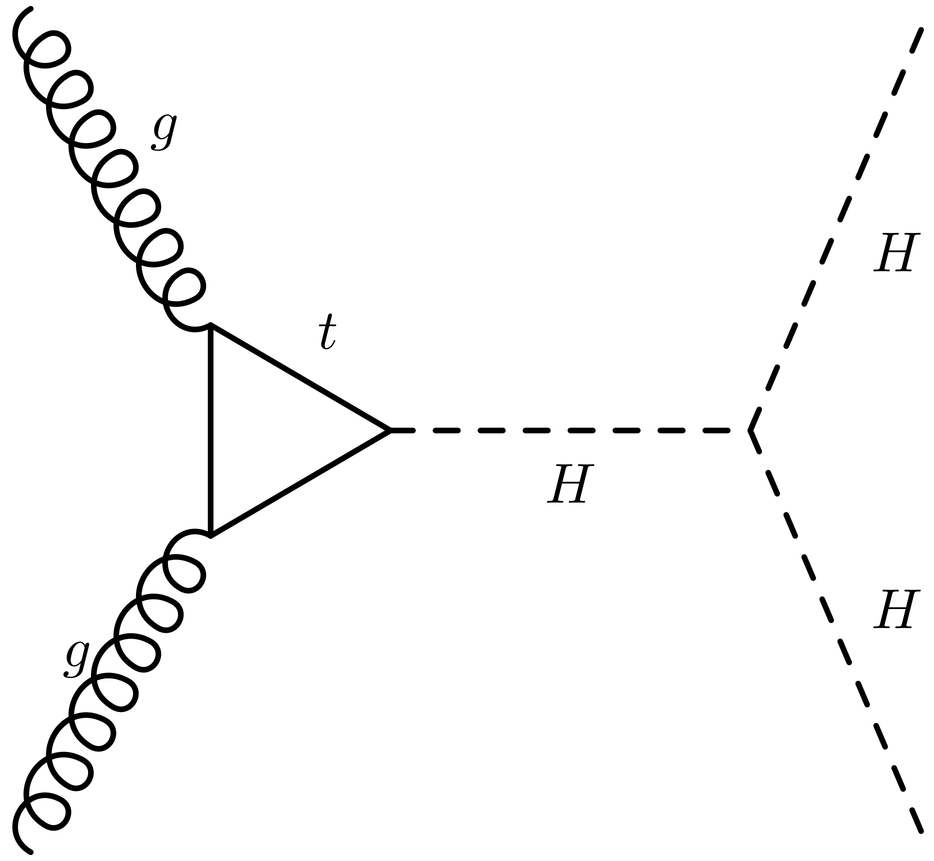
Why di-Higgs

The measurement of the Higgs boson **self coupling** is a **fundamental** test of the SM

SM predicts a **extremely small cross section** for HH production (~30 fb at 13 TeV)

1000 times smaller than the single Higgs boson production



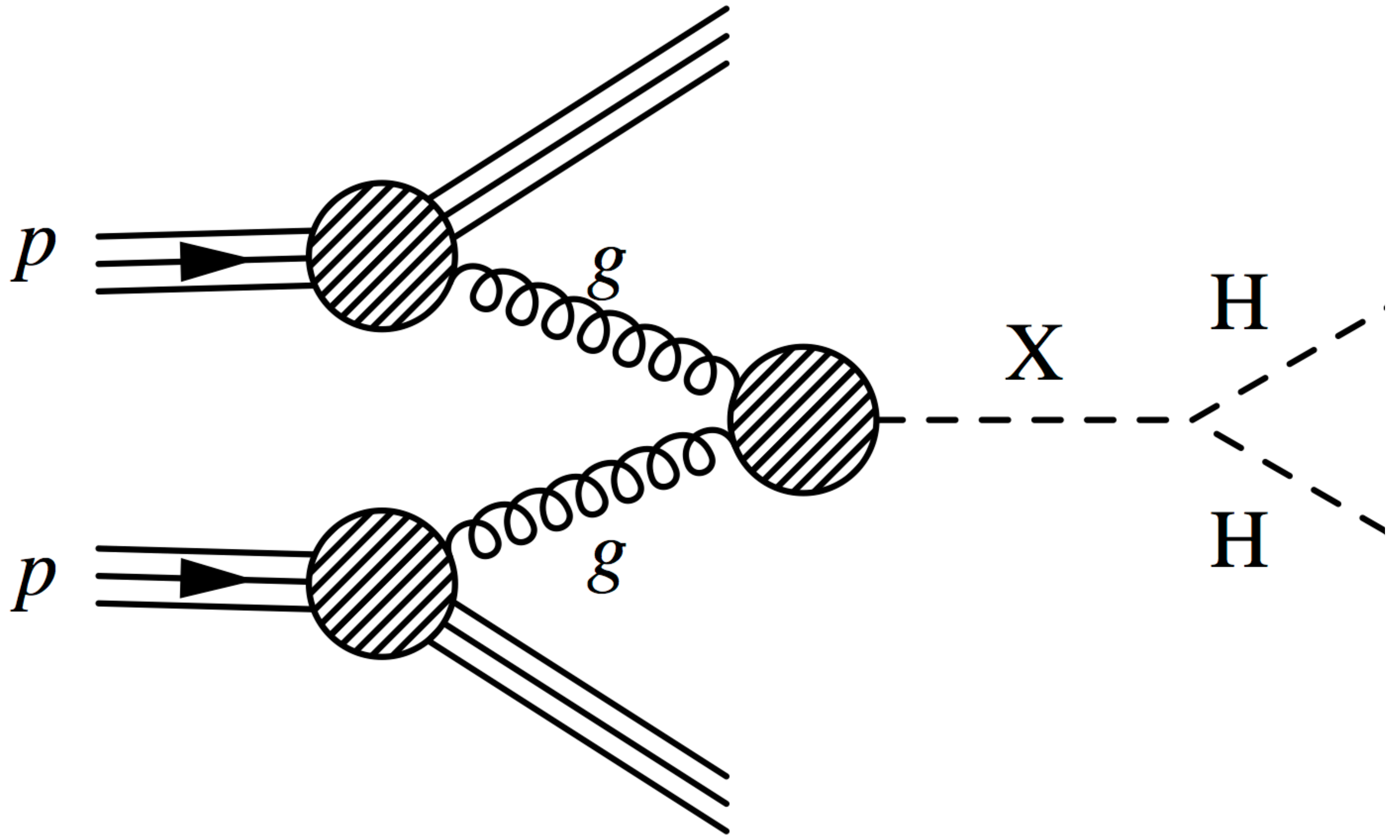


λ_{HHH}

But, it is significantly enhanced in many BSM scenarios

Why di-Higgs

- Gluon fusion production of a massive X - **resonant HH** state
    - **small natural width**
- Depending on the resonance mass different models can be probed:
    - The mass range around 300-500 GeV is interesting for **(N)MSSM**
    - From 500 GeV it is interesting for **warped extra dimensions** models
        - spin-0 Radion and spin-2 KK-Graviton



Higgs, as a new powerful tool to search for new physics

hh resonant production

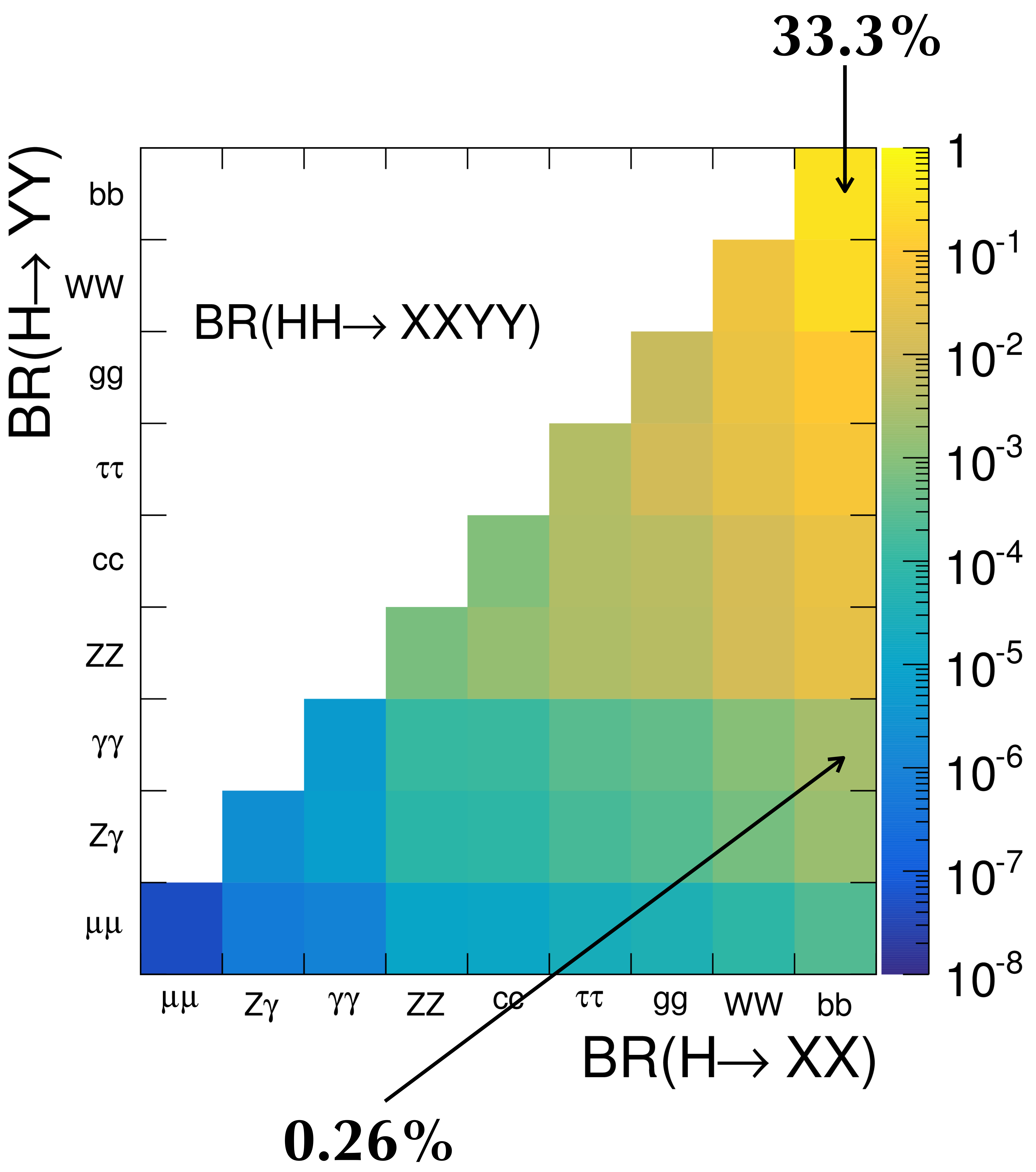
h(γγ)

simple topology
excellent mass resolution
clean final state for low mass resonances
Limited by small BR

h($b\bar{b}$)

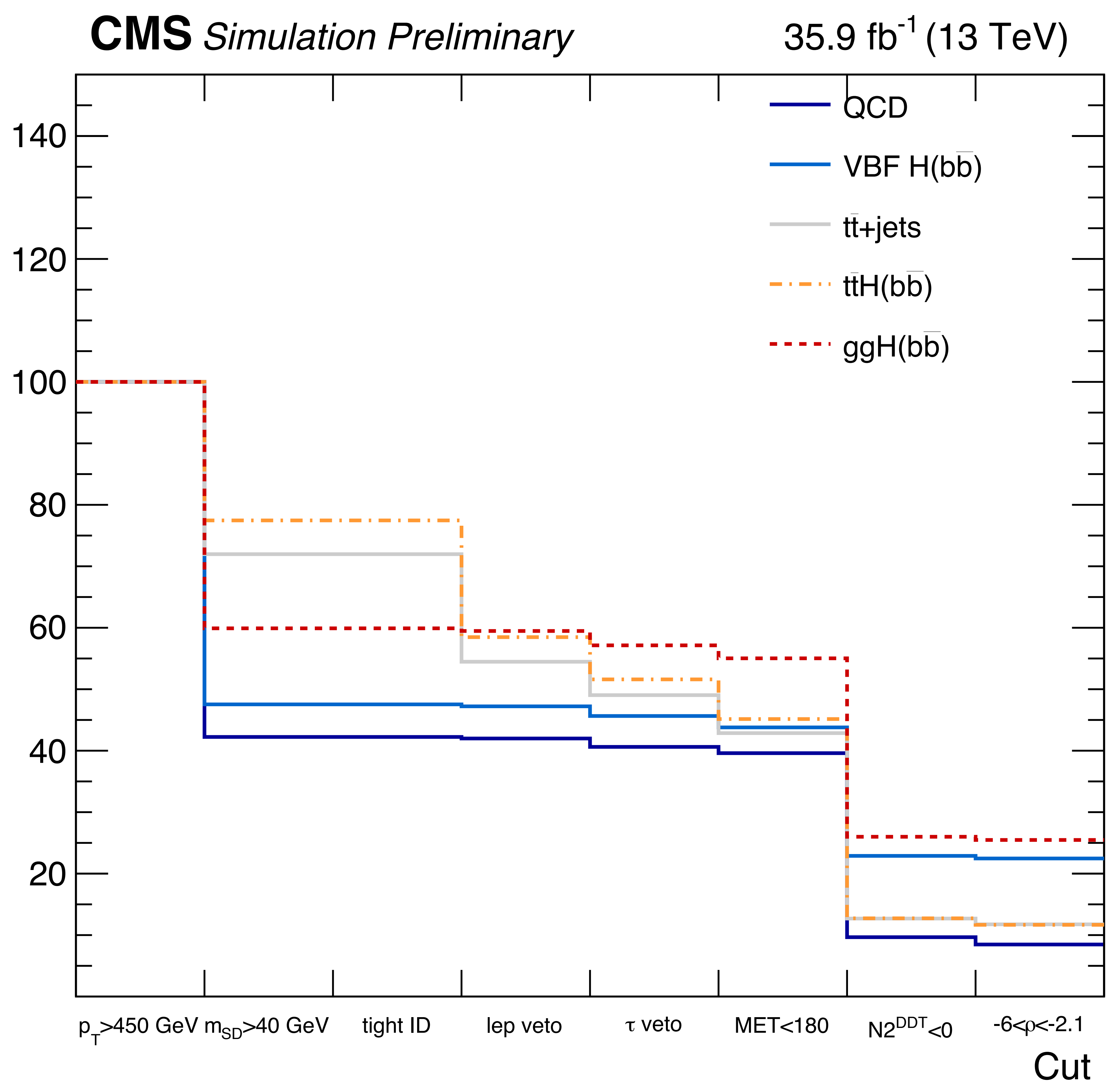
highest BR: larger statistics
high b-tag efficiency and low fake rate
multi-light jets background is highly reduced

Identifying b-quarks plays a critical role



Event Selection

- Highest p_T AK8 jet with Puppi inputs:
  - $p_T > 450$ GeV $|\eta| < 2.5$, tight PF jet ID
  - jet soft-drop mass > 40 GeV ($z = 0.1$, $\beta = 0$)
  - **Substructure**: two prongs discrimination
    - $\mathbf{N2^{DDT}}$ @ 26% background efficiency,
  - **double-b tagger** > 0.9
    - @30% sig. efficiency; 1% bkg efficiency
- **Lepton veto**
- **tt+jets rejection**:
  - Puppi MET < 180 GeV
- **ρ=** $\log(m_{SD}2/p_T2)$ **range $-6.0 < \rho < -2.1$.**
  To avoid instabilities at the edges of the distribution, due to finite cone effects from the AK8 jet clustering (around $\rho \sim -2$), and to avoid the non-perturbative regime of the soft drop mass calculation (below $\rho \sim -6$).
  - At p_T =450 GeV, ρ=-2.1 corresponds to $m_{SD} \sim 166$ GeV; ρ=-6 corresponds to $m_{SD} \sim 22$ GeV;

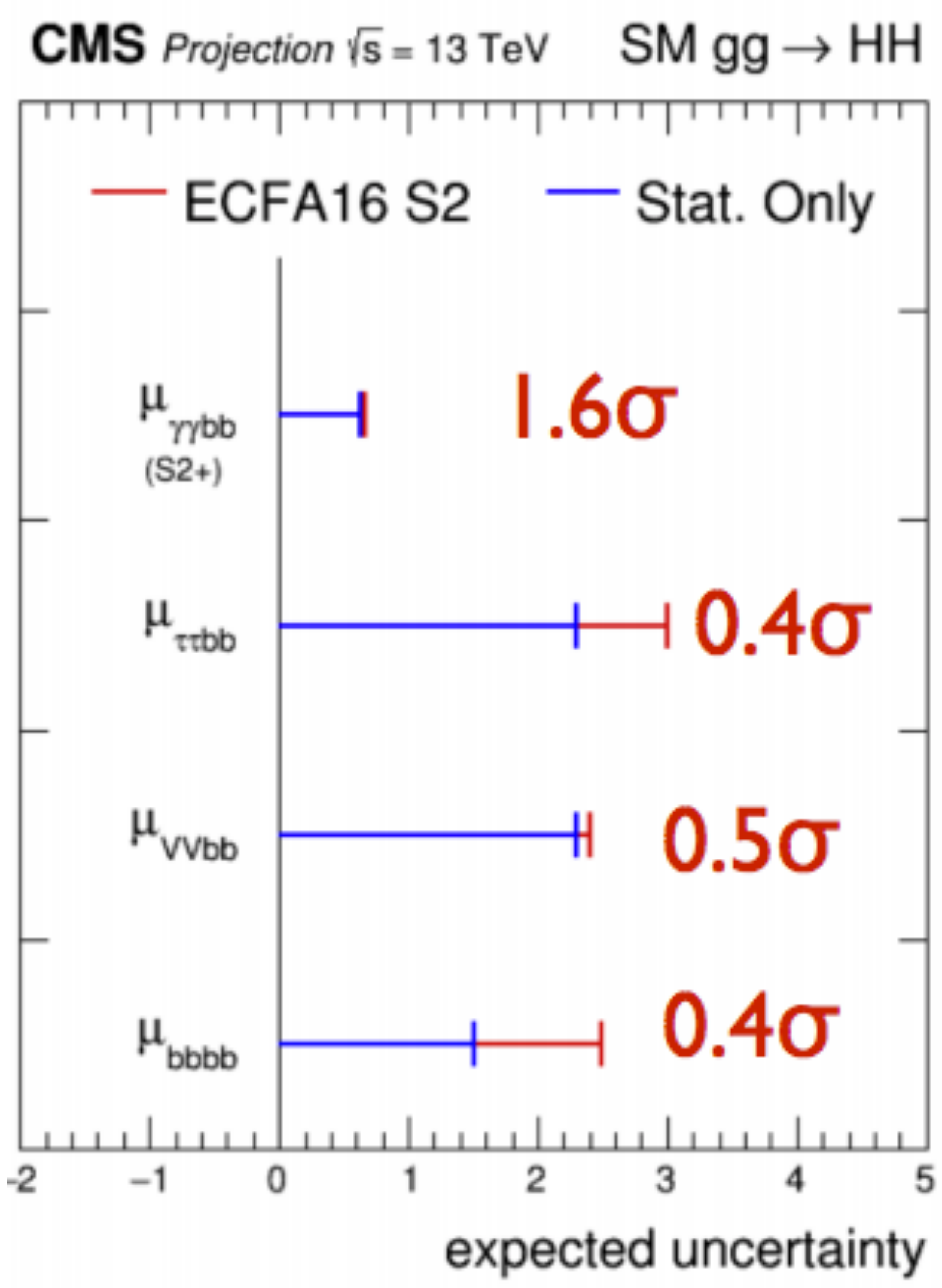


Systematics Uncertainties

Systematic uncertainty source	Type (shape/normalization)	Relative size (or description)
QCD transfer factor	both	float polynomial coefficients $a_{k\ell}$ and QCD normalization
Luminosity	normalization	2.6%
V-tag ($N_2^{1,DDT}$) efficiency	normalization	4.3%
Muon veto efficiency	normalization	0.5%
Electron veto efficiency	normalization	0.5%
Trigger efficiency	normalization	4%
Muon ID efficiency	shape	up to 0.3%
Muon isolation efficiency	shape	up to 0.2%
Muon trigger efficiency	shape	up to 15%
$t\bar{t}$ normalization SF	normalization	from 1μ CR: 8%
$t\bar{t}$ double-b mis-tag SF	normalization	from 1μ CR: 15%
W/Z NLO QCD corrections	normalization	10%
W/Z NLO electroweak corrections per p_T category	normalization	15% – 35%
W/Z NLO electroweak ratio decorrelation per p_T category	normalization	5% – 15%
Double-b tagging efficiency	normalization	4%
Jet energy scale	normalization	up to 10%
Jet energy resolution	normalization	up to 15%
Jet mass scale	shape	shift m_{SD} peak by $\pm 0.4\%$
Jet mass resolution	shape	smear m_{SD} distribution by $\pm 9\%$
Jet mass scale p_T	normalization	0.4%/100 GeV (p_T)
Monte Carlo statistics	normalization	-
H p_T corr (ggH)	normalization	30%

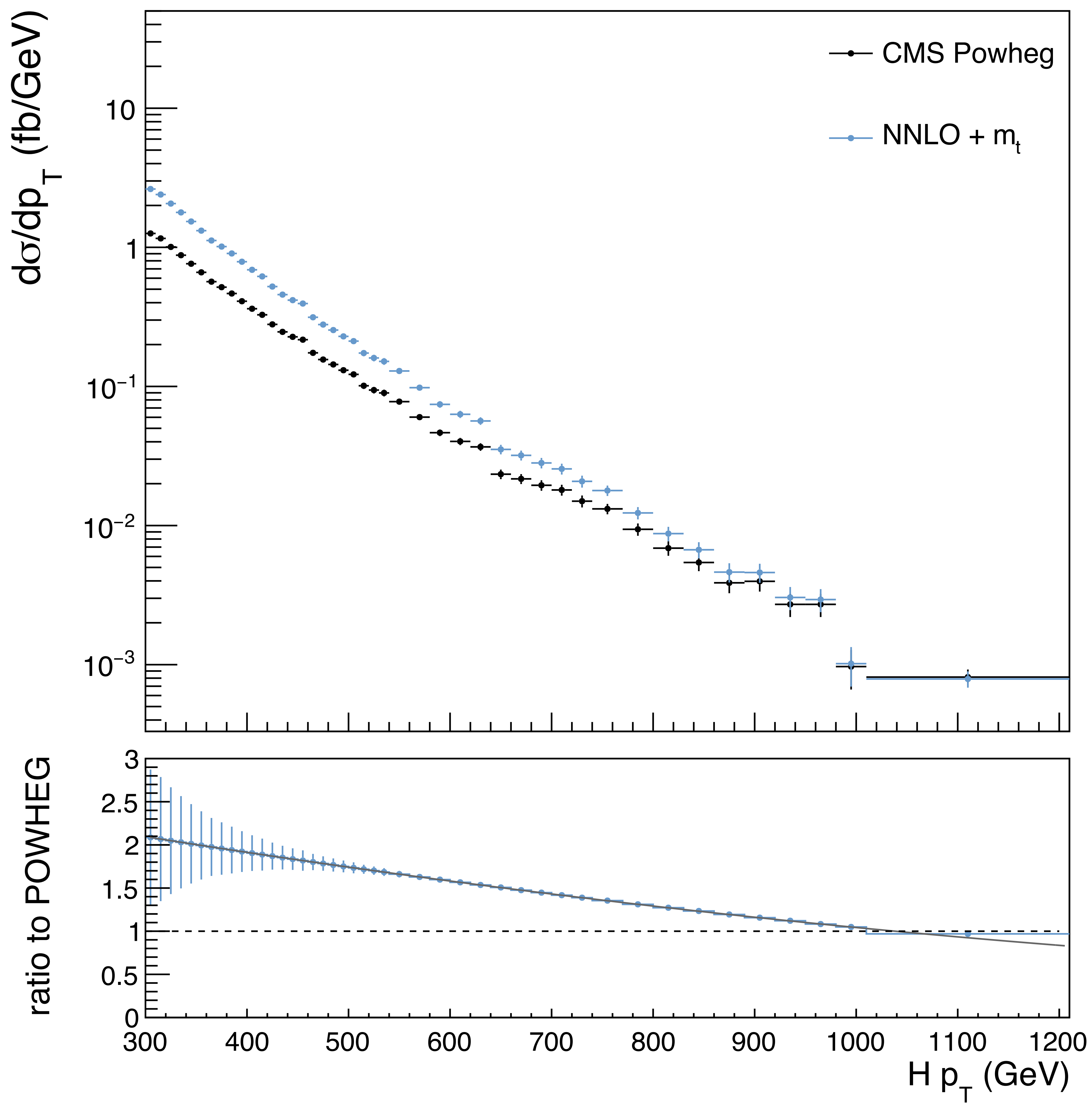
Perspectives

- Extrapolation from Run II to HL-LHC (3000 fb-1) SM HH production
  - but also analyses improve fast



ggH Higgs p_T reweighting finite m_t + NNLO

- CMS default for ggH is Powheg (*)
- To account for both the effects of higher order corrections and for the finite top mass loop a multi-correction approach is adopted
- Two separate effects: finite top mass corrects ***down***, N(N)LO corrects ***up***
- Estimate k-factor of ~1.6 for Higgs $p_T > 450$ GeV wrt the Powheg sample
- We adopt a 30% uncertainty following the addition in quadrature of the NNLO and NLO* uncertainties.



(*) *is generated with Higgs matrix elements up to 1 jet assuming the infinite top mass approximation (mtop → ∞)*

Transfer factor for the QCD prediction

- If the double-b tag discriminator value were completely uncorrelated from the jet p_T and m_{SD}, the transfer factor would be equal to unity.
- To account for deviations from unity, we Taylor expand ***F*** in ρ and p_T

$$\boldsymbol{F(\rho, p_T)} = ((1 + a_{01}\, p_T + a_{02}\, p_T^2 + \cdots)$$
$$+(a_{10} + a_{11}\, p_T + a_{12}\, p_T^2 + \cdots)\rho$$
$$+(a_{20} + a_{21}\, p_T + a_{22}\, p_T^2 + \cdots)\rho^2 + \cdots$$

We performed the F-test on the blinded, full 2016 dataset to decide the degree of the polynomial form:

- ($n_\rho = 2$, $n_{p_T} = 1$) polynomial is the default